Survey on

Fault Tolerance for Link Failure in Wireless Mesh Networks

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ABSTRACT

Wireless mesh networks (WMNs) have gained considerable attention in the recent years due to fast deployment, easy maintenance and low upfront investment compared with traditional wireless networks.

Since WMNs are typically used as wireless backbones, they have the nature that the wireless communication is not stable. Hence, it is significant to protect them against link or node failures. This survey provides comprehensive research on the issue of fault tolerance of link failure in WMNs. In this survey, we present our investigation of the classification of fault-tolerence approaches in different types of WMN. We put the emphasis on approaches which make WMN immune from link failures.

Keywords: wireless mesh network (WMNs), fault tolerance, link failure

CONTENTS

1. INTRODUCTION

Wireless mesh networks (WMNs) is an emerging technology that uses wireless multi-hop networking to provide a cost-efficient way for community or enterprise users to have broadband Internet access and share network resources [Akyildiz and Wang 2005]. The major components of a WMN include wireless mesh routers and wireless mesh clients. Due to its fast deployment, easy maintenance and low upfront investment compared with the traditional wireless networks, WMN has gained considerable attention in recent years. There are many applications based on WMNs, such as the Portsmouth Real-time Travel Information System (PORTAL) which is used to provide real-time travel information to passengers, broadband home networking, and so on.

Since WMNs are typically used as wireless backbones, they have the nature that the wireless communication is not stable. Hence, it is significant to protect them against link or node failures. In this survey, we only consider those approaches that resolve the problem of link failures.

There are three main classes of approach to recover from link failures: protection schemes, restoration schemes and hybrid schemes. Protection schemes reserve backup resources in advance and can be classified into two categories: proactive protection and reactive protection. On the contrary, restoration schemes are trigged only after a failure is detected and then they start to discover the available resources. The hybrid schemes resort to restoration when the protection fails. However, in this survey, we will introduce these approaches in terms of the classification of the WMNs: basic WMNs and multi-radio and multi-channel WMNs. There are 13 approaches introduced in the former group and 7 ones in the later one.

The rest of the survey is organized as follows: we will overview the WMN and the link failures and the basic solutions for them in Section 2. Section 3 presents recent approaches for recovering from link failures. Section 4 draws our conclusion. The References section lists the full bibliography and the Appendix contains all annotated bibliography of 20 selected papers.

2. GENERAL DISCUSSION

2.1 Overview of Wireless Mesh Networks

There are two types of nodes in WMNs: mesh routers and mesh clients. All of the nodes in WMNs are considered as a host and a router. They leave the data which are forwarded to themselves and transmit the data which are for others. Therefore, the data will be kept forwarding until they arrive at the destination. Compared with traditional wireless networks, such as ad hoc networks, WMNs have the following main features: first, the mesh routers are relatively stationary, hence, the routing paths can be created that are likely to be stable; second, all traffic is either to or from a designated gateway which connects the WMNs to the Internet; third, the power consumption of the mesh routers is not significant; finally, many security issues can be neglected since the system is created in a single domain.

WMN has gained considerable attention in recent years not only due to its fast deployment, easy maintenance and low upfront investment compared with traditional wireless networks, but also its support of the existing wireless networks, such as wireless sensor networks, wireless fidelity network (Wi-Fi), and so on. Moreover, it is reliable and offers redundancy. When there is a link loss or node failure, the nodes can still communicate with each other by using other intermediate nodes. Hence, WMN is dynamically self-organized and self-configured. To date, WMNs are applied in many applications such as enterprise networking, building automation, and broadband home networking.

However, there is still more work to do to show the true capability of WMNs. In this survey, we focus on the investigation of multicast routing in WMNs.

2.2 Definition of The Problem

Since WMNs are typically used as wireless backbones, they have the nature that the wireless transmission is not stable. However, the nodes in WMNs do not move, and the route failure is most probably caused by power-off or system failure. Generally, there are two types of failure: node failure and link failure. Link failure happens more frequently than node failure and node failure always contains multiple link failures since the link

will fail on a failed node. In this survey, we only investigate the approaches for link failures.

Link failure can be classified into two categories in terms of the number of broken links: single-link failure and multiple-link failure. Moreover, according to the recovery time from the link failure, they can be classified as permanent failure and transient failure [Wu et al. 2003]. When a failure does not recover automatically within a short time, we call it a permanent failure. While a failure lasts for a very short duration, we call it a transient failure. Temporary failures are more frequent than permanent ones.

2.3 Overview of Fault-Tolerence Approaches

There are three main classes of approach to recover from link failures: protection schemes, restoration schemes and hybrid schemes [Al-Kofashi and Kamal 2007].

In the protection scheme, such as [Srinivas and Modiano 2003], [Li and Hou 2004], [Zhao et al. 2006], [Al-Kofashi and Kamal 2007] and [Zhao et al. 2007], two (or more) link-disjoint paths are selected between a source and a destination node. The source node forwards the data on all of the selected paths. If there is a link on one of the paths which is broken, the destination can still receive the data for the other path. Currently, most mentioned protection schemes are referred to as 1+1 protection schemes. The protection schemes can be classified into two categories: proactive protection and reaction protection. The most difference between these two classifications is that data is forwarded to the destination along the selected paths at the same time in the former one, hence it needs at least twice as many resource which is hard to realize; while in reaction protection, there are primary path and the backup path, the backup path is not used until a failure happens.

Restoration schemes are more capacity-efficient, which are used in [Lumetta and Medard 2001], [Wu et al. 2003], and [Dong et al. 2005]. When a failure is detected, it switches the failed path to a backup path dynamically. Many connections can share the fibers used in the backup route. However, since restoration introduces some delay in the recovery process, it should balance capacity-efficiency and speed. There are two kinds of restoration algorithm: one is a dynamic algorithm in which plentiful message flooding is needed to recompute the route, hence, it is fast enough to address frequent failures but

introduces delay; the other one is a pre-planned algorithm which can recover from the failure more quickly.

Hybrid schemes resort to restoration when the protection fails.

3. SURVEY OF RESEARCH

In this section, we will introduce the approaches to fault tolerance for link failure in different types of WMNs. We classify the WMNs as basic WMNs, and the ones with multi-radio or multi-channel.

3.1 Approaches for Basic WMNs

3.1.1 Approaches for Basic WMNs

Since some approaches do not indicate clearly the specific scenario they are used for, we classify them in this category too. All of these approaches not only resolve the problem of providing fault-tolerance but also consider some other problems in the existing techniques. We will introduce them in the following.

[Young 1998] and [Kabata et al. 2001] present approaches to establish network-wide synchronization, but these approaches cannot handle the failure of master nodes. Hence, [Tabata et al. 2003] present a new scheme which not only establishes synchronization autonomously without centralized control in wireless networks but also handles the link failure in WMNs.

In 2001, [Lumetta and Medard 2001] state that multiple failures should be considered in failure localization. However, most existing recovery algorithms only consider a single link or node failure. Hence, they present a quantitative measure of a network's ability to recover from two-link failure by investigating the relationship between failure localization and the properties of link restoration algorithms. Moreover, they introduce a genetic algorithm and classification schemes for 3 types of two-link failures. They claim that the proposed schemes can recover from most types of two-link failures.

[Wu et al. 2003] also argue that the distributed pre-planned techniques cannot handle all cases of multiple failures since they only have local knowledge but not global knowledge. Therefore, they propose a restoration scheme called the Hybrid Fast

Restoration Scheme (HFRS) in which both local and global restorations are used. Its main idea is the recovery strategy for local failure. The single link, multiple links and single node failure can be handled by using HFRS.

In 2004, [Lee and Ward 2004] claim that though the existing ad hoc routing protocols such as DSR and AOVD can be utilized in WMNs, their performance is not the best since some assumptions in ad hoc network are not true in WMNs. Therefore they propose a protocol which considers the problem of load-balancing and fault tolerance in WMNs. This protocol is a shortest-path load-balancing diverse routing protocol by utilizing quasi-xy-routing algorithm. It provides robustness and the authors claim that it outperforms the traditional ad hoc protocols.

[Nelakuditi et al. 2005] also take multiple link failures into account. They state that it is hard for the previous routing approaches, such as an algorithm proposed by [Narvaez et al. 1999], HSLS [Santivanez et al. 2001], FSR [Gerla et al. 2002] and failure insensitive routing approach [Lee et al. 2004], to resolve multiple link failures. Hence, they present a new scheme called BAF, in which the trade-offs of its reliability, optimality and scalability is balanced, to deal with multiple link failures. Based on the BAF, the authors propose other two routing schemes called BAFL and FBAF.

In 2005, besides pairing the link failures, [Hsiao and Kung 2005] consider the problem of the routing message overhead and end-to-end control delay in the wireless networks. They state that though some approaches are presented to resolve these problems, such as the algorithms proposed by [Park and Corson 1997], [Nasipuri et al. 2001] and [Ganesan et al. 2001], they are complicated and difficult to deal with. Hence, they provide a mesh construction algorithm called “beam-crossing grids”. By using this algorithm, two wireless mesh networks can work in parallel without interfering with each other. When there is a failure, the backup network will be used; if not, the multiple mesh networks will work in parallel to expand the bandwidth of the networks.

[Carlson et al. 2005] take Quality of Service (QoS) into consideration. They state that the original Distributed Coordination Function (DCF) cannot handle real time applications which need low and stable packet delay and constant throughput. Moreover, the existing reservation mechanisms cannot deal with failures and the reserved path maybe break. Therefore, they propose an end-to-end reservation protocol called DARE. It

is an end-to-end protocol and periodically reserves occurring time slots in the nodes in a distributed manner.

[Das et al. 2007] also consider the problem of QoS. They state that the priorities of flows are assigned statically based on QoS requirements and schemes are probabilistic and cannot provide service plan effectively in the traditional work. After studying off-the-shelf solutions and the optimal scheduling solution proposed by [Salem and Hybaux 2005], they provide a system called APOLLO to dynamically guarantee the individual client fairness, specifically the "bitrate-for-bucks" service. APOLLO maintains the simplicity of off-the-shelf and performs practical scheduling of packet transmission.

3.1.2 Approaches for Unicast in WMNs

Biswas and Morris have provided the concept of opportunistic routing for wireless mesh networks in 2002 and 2005, which exploits the independent reception of transmissions at different nodes. However, it does not address the problem of resilience. [Yuan et al. 2005] propose a resilient and opportunistic routing protocol for wireless mesh networks which is called ROMER. ROMER ensures resilience against link failure and node failure. Its main idea is to use credit mechanism to build a path between the source node and destination node.

However, [Zhao et al. 2006] claim that ROMER is designed for unicast scenario and it does not work in the multicast scenario.

We will investigate recovery approaches available in the multicast WMNs in the next part.

3.1.3 Approaches for Multicast in WMNs

[Banerjee and Misra 2002] provide an energy-efficient approach for wireless communication. However, it is based on the reliable link layers. Hence, [Dong et al. 2005] propose two centralized and one distributed algorithm called BAMER, GAMER and DAMER respectively and claim that they are the first to provide reliable and energy efficient transmission in the unreliable link layer in WMNs.

Moreover, little attention is paid in the literature to the issues of protecting the multicast groups against link or node failures. [Zhao et al. 2006] claim that they are the first to do research on this problem. In order to gain the goal, they propose a resilient

forwarding approach called resilience forwarding mesh (RFM), in which two node-disjoint paths between the source-destination pair by using the advantage of wireless broadcast. Moreover, they propose four heuristic algorithms called node-disjoint tree algorithm (NDT), revised node-disjoint tree algorithm (RNDT), shared disjoint mesh algorithm (SDM) and minimal disjoint mesh algorithm (MDM) to find the approximate solutions of RFM. The former two are tree-based algorithms and the later two are mesh-based algorithms. They claim that RFM can protect the multicast group efficiently in WMNs and MDM is the best one out of all of the proposed algorithms.

Later in 2007, they proposed another scheme called Probabilistically Reliable Multicast Routing (PRMR) to enhance the reliability of multicast routing in WMNs. This scheme is based on the RFM approach and the directional link packet delivery rate is considered as the metric of choosing the next forwarding nodes. They claim that PRMR can increase reliability efficiently.

Since the traditional proactive and reactive protection schemes are with limited resource or bring in a delay, [Al-Kofashi and Kamal 2007] present a new approach to protect many-to-one flow networking against link failure by using network coding. They claim that they are the first to use this technique in this area.

3.1.4 Summary

In this section we have summarized some approaches which can be used to repair link failures in basic WMNs. Table I shows the list of the papers we have discussed in this section.

Year	Author	Title	Major Contribution
2001	Lumetta and Medard	Towards a Deeper Understanding of Link Restoration Algorithms for Mesh Networks	A scheme to repair most of two-link failures in WMNs
2003	Tabata et al.	A Study on the Autonomous Network Synchronization Scheme	A scheme that provides the synchronization without centralized control and recovering

		for Mesh Wireless Network	from link failures in WMNs
2003	Wu et al.	Fast Restoring Gigabit Wireless Networks Using a Directional Mesh Architecture	A scheme which detects and repairs transient node and multiple link failures in directional WMNs
2004	Lee and Ward	A Study of Routing Algorithms in Wireless Mesh Networks	A protocol that addresses the problem of load-balancing and fault tolerance in WMNs
2005	Carlson et al.	A Distributed End-to-End Reservation Protocol for IEEE 802.11-Based Wireless Mesh Networks	A protocol which provides a reliable and efficient support for QoS applications
2005	Dong et al.	Minimum Energy Reliable Paths Using Unreliable Wireless Links	Three algorithms that first provide reliable and energy efficient transmission in the unreliable link layer in WMNs
2005	Hsiao and Kung	Constructing Collocated Non-Interfering Wireless Meshes with Beam-crossing Grids	An algorithm which provides not only a simultaneously usable, but also a fail-safe WMNs
2005	Nelakuditi et al.	Blacklist-Aided Forwarding in Static Multihop Wireless Networks	An approach which addresses the problem of enhancing the salability of networks and handling with multiple link failures
2005	Yuan et al.	ROMER: Resilient Opportunistic Mesh Routing for Wireless Mesh Networks	A protocol that provides resilience against lost wireless links, channel outages and node failures and the high throughput
2006	Zhao et al.	Protecting Multicast Sessions in Wireless Mesh	An approach that first protects the multicast groups against node or

		Networks	link failures in WMNs
2007	Al-Kofashi and Kamal	Network Coding-Based Protection of Many-to-One Flow Networks	An approach that first protect the many-to-one flows in WMNs and MSNs
2007	Das et al.	Practical Service Provisioning for Wireless Meshes	A system which provides a guarantee of individual client fairness
2007	Zhao et al.	A Scheme for Probabilistically Reliable Multicast Routing in Wireless Mesh Networks	A scheme which enhances the reliability of the multicast routing in WMNs

Table I

3.2 Approaches for Multi-radio and Multi-channel WMNs

3.2.1 Approaches for Multi-radio WMNs

When the mesh router is equipped with multiple radios, the traffic in the WMN is divided into two types: one is routing and configuration between mesh routers, the other is the access to the network on a different radio. [Bahl et al. 2004] claim that using multi-radio technologies can be considered as a viable solution to the problem of improving link capacity and reliability in WMNs due to the diminishing cost of hardware. In addition, they state that existing single wireless platforms with a single radio cannot satisfy the increasing demand. Hence, the authors design a multi-radio wireless platform which resolves five problems in WMNs which are as the followings: energy management, capacity enhancement, mobility management, failure recovery and last-hop packet scheduling.

[Raman and Chebrolu 2005] take long-distance links into consideration. They state that that the 802.11 CSMA/CA MAC is not efficient for WMNs with long-distance links. Though some technologies can be used to improve this situation, they have a high cost. Therefore, they present a new protocol called 2P based on SynTx/SynRx [Raman and Chebrolu 2004]. It operates on the link by making all interfaces coordinate their switch between SynRx and SynTc in which the temporary loss of synchrony and recovery from a

link failure are resolved.

[Kim et al. 2007] also indicate that there are some problems in the previous channel-related research of WMNs, which are: overhead is high and scalability is limited, difficulty in obtaining accurate information in dynamic networks, QoS failures may be caused when failure is repaired, more resources compared with the reconfiguration are requited when some fault-tolerance routing protocols such as local re-routing [Nelakuditi et al. 2005] and multi-path routing [Chen et al. 1999] are used. Therefore, they propose an algorithm called LEGO to overcome the above-mentioned problems. There are three phases in LEGO: monitoring, reconfiguration and planning, which make the multi-radio of WMN to recover from the local link failures available.

In 2007, [Pirzada et al. 2007] first work on the problem of discovering and exploiting multiple bidirectional links between a node and its neighbor nodes in WMNs. They present a new protocol called AODV-ML which is an extension of AODV. Two phases are used to discover multiple links in AODV-ML. They also state that the additional links established via AODV-ML can be used for applications such as the followings: link repairing, link optimization, load-balancing and striping.

Later in 2008, [Mir et al. 2008] indicate that AODV cannot distinguish between the mesh routers and mesh clients, minimize co-channel interference and maximize the use of multiple orthogonal channels between the source-destination pair. Therefore they propose a new protocol called HOVER based on AODV. HOVER has the same route discovery mechanism as AODV-MR and 3 new mechanisms. The authors claim that HOVER can establish a path fast and then change it to a better path which reduces the path creation delay. Moreover, they state that HOVER can repair a link failure by switching the failed route to another valid route.

3.2.2 Approaches for Multi-channel WMNs

There are two ways to improve the scalability of WMNs: one is to enhance the existing MAC protocol or propose new ones, the other is to provide multi-channel in each node in the network which can also enhance the capacity of the network. Due to the decreasing cost of hardware, people started to work on the technologies of using multi-channel to improve the performance of WMNs.

In 2007, [Zeng and Zeng 2007] utilize multiple channels to improve the throughput of the network. They propose bandwidth guaranteed shortest path scheduling, in which a distributed algorithm and a TDMA is used. Moreover, they present an algorithm based on the k-shortest path. There are three phases in the algorithm: route discovery, route reply, and route maintenance in which link failure can be recovered.

3.2.3 Approaches for Multi-radio and Multi-channel WMNs

In this part of the survey, we will introduce the approach used in multi-radio and multi-channel WMNs in which each node contains multiple radios and each radio has multiple channels.

[Tsai and Moors 2007] propose a new path selection metric called WIM which is based on the ETT metric and interference minimization. WIM can provide reliability routing in multi-radio, multi-channel wireless mesh networks by selecting multiple routing paths. They claim that that WIM can provide higher reliability and lower delay than MD path selection and CAM.

3.2.4 Summary

In this section we have summarized some approaches which can be used to repair the link failures in the multi-radio and multi-channel WMNs. Table II shows the list of the papers we have discussed in this section.

Year	Author	Title	Major Contribution
2004	Bahl et al.	Reconsidering Wireless Systems with Multiple Radios	A multi-radio network platform which improves the performance of energy management, capacity enhancement, mobility management, failure recovery and last-hop packet scheduling
2005	Raman and Chebrolu	Design and Evaluation of a new MAC Protocol for Long-Distance 802.11 Mesh Networks	A protocol which improves the performance of 802.11 without much additional overhead

2007	Kim et al.	Extended Abstract: Self-Healing Multi-Radio Wireless Mesh Networks	An algorithm that addresses the problem of repairing local link failures in multi-radio WMNs
2007	Pirzada et al.	Multi-Linked AODV Routing Protocol for Wireless Mesh Networks	A protocol which first takes the problem of discovering and exploiting multiple bidirectional links in WMNs into account
2007	Zeng and Zeng	An Efficient Scheme for Solving Bandwidth Guaranteed Scheduling and Shortest Path Routing Problem in Wireless Mesh Networks	A scheme and an algorithm which addresses the problem of interference aware bandwidth guaranteed scheduling and choosing shortest path routing in multi-channel WMNs
2007	Tsai and Moors	Interference-Aware Multipath Selection for Reliable Routing in Wireless Mesh Networks	A metric which provides reliability routing multi-radio, multi-channel wireless mesh network
2008	Mir et al.	HOVER: Hybrid On-demand Distance Vector Routing for Wireless Mesh Networks	A protocol which improves the performance of packet delivery and latency in Hybrid WMNs

Table II

4. CONCLUDING COMMENTS AND FUTURE WORK

With the emergent applications for multicast data aggregation and dissemination, recovering from link failures is one of the most significant issues in WMNs. In this survey, we have reviewed the WMNs, link failures in WMNs, and the solutions for them. In addition, most of the introduced solutions not only resolve the problem of recovering from link failures, but also improve the performance of the WMNs, such as load-balancing, consumption energy, capacity, bandwidth, packet delivery, latency and delay.

We have classified all of the approaches into two groups in terms of the two main types of the WMNs: basic WMNs and multi-radio multi-channel WMNs. There are thirteen approaches introduced in the former group and seven in the later one.

We would like to mention that the fault-tolerance field in WMNs is still active and many new approaches are being proposed. [Lumetta and Medard 2001] state that they will work on the strategies for switching existing connections from the lost links due to a failure to protected links and investigate the interaction between link restoration and the recovery algorithms. [Zeng and Zeng 2007] state that they will do research on multicast routing for bandwidth guaranteed scheduling and routing problems. [Kim et al. 2007] claim that they will they will optimize both channel and flow assignments, and the measure the link failure characterization in multi-radio WMNs.

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APPENDIX

ANNOTATED BIBLIOGRAPHY

[Al-Kofashi and Kamal 2007]

- Previous work referred to: The authors state that the traditional proactive or reactive protection schemes are with limit resource or bring in a delay. They are the first to use network coding as a proactive protection to protect many-to-one flow networking.
- Problem to be resolved: This paper addresses the problem of the protection to many-to-one flows in WMN and MSNs.
- New approach carried out: The authors propose an approach which is based on the network coding. They claim that the approach creates n+1 paths from n data units and then forward these combinations. Hence, when a path is loss due to link failure, the destination can be recovered. Moreover, the authors provide three generalizations for the problem and introduce how to make the linear independence between linearly combined data units available by utilizing {0, 1} coefficients in which two algorithms are used. In addition, they formulate the problem of source grouping as an MILP.
- Analysis carried out: The authors consider the limited minimum cut in the networks. They state that if the number of the minimum edge cut is greater than or equal to n+1, the proposed approach can be used directly, or the formed combinations should be rewritten before forwarded. They also claim that not only fairness but also network resources should be considered to choose the optimality of the chosen group. Hence, they state that the optimality group can be determined by two parts: the degree of disjointedness of the chosen group and the degree of the resource utilization.
- Conclusion: The authors state that the proposed approach can protect the many-to-one flow at the speed of proactive protection, but at the cost of reactive protection.
- Future work: The authors state that the detail of the implementation of the proposed approach in terms of the required number of slots and the scheduling strategies will be contained in their future work.

[Bahl et al. 2004]

- Previous work referred to and Problem to be resolved: The authors state that the existing single wireless platforms cannot satisfy the increasing demand since only a single radio or, in a few cases, multiple radios are used. They claim that using multiple radios in wireless system can improve system performance and functionality. Hence, the authors present the solutions to five standard problems in wireless networks by using the multi-radio wireless platform. The five problems are as the followings: energy management, capacity enhancement, mobility management, channel failure recovery and last-hop packet scheduling.
- New system carried out: The authors introduce three design guidelines for the new system: design for choice, flexibility and separation. Before presenting the solutions for the mentioned problems, they assume that the spectrum and channel capacity are limited and the cost of adding radio will decrease. They proposed three approaches, Alert-on-LPR, Control-on LPR and Data-on-LPR, to reduce the energy consumption and rise the battery lifetimes of the mobile devices. Moreover, they present multi-radio unification protocol (MUP) and multi-radio link quality source routing (MR-LQSR), in which they propose a new metric called Weighted Cumulative Transmission Time (WCETT), to enhance the capacity of the networks. The authors also state that with proper design, the network can achieve a handoff with zero packet loss. In addition, they claim that channel errors can recover by building appropriate radio switching logic.
- Experiment carried out: The authors evaluate the performance of proposed approaches for the 5 mentioned problems respectively.
- Results obtained: The authors state that the experimental results show that Alert-on-LPR can obviously increase the standby time of a PDA-based phone and the Data-on-LPR can save 40% energy than the power-save mode of 802.11. They also state that the results of the throughput of CDF show that the throughput increases by over 70% when all houses have two radio and increase by nearly 30% when half the house have two radios. They claim WCETT perform better than ETX and minimum hop-count. Moreover, they state that the 2.4GHz phone can still work on a multi-radio wireless Lan when there is a channel error happened.

- Conclusion: The authors claim that the proposed multi-radio network platform can provide obvious improvement for wireless system.
- Papers that refer to this paper:

  This paper has 82 citations on google scholar. Only one is related to this survey which is as the following:

  TSAI, J.W. AND MOORS, T. 2007. Interference-Aware Multipath Selection for Reliable Routing in Wireless Mesh Networks. *Mobile Adhoc and Sensor Systems 2007. MASS 2007. IEEE Internatonal Conference on*. 1-6.

[Carlson et al. 2005]

- Previous work referred to and Problem to be resolved: The authors state that the real time applications need low and stable packet delay and constant throughput. However, this Quality of Service (QoS) is not provided by the original Distributed Coordination Function (DCF). Moreover, the existing reservation mechanisms cannot handle failures and the reserved path maybe break. This paper addresses this problem in end-to-end, interference-protected, failure-handling and low-overhead protocol.
- New protocol carried out: The authors propose a protocol called Distributed end-to-end Allocation of time slots for Real-time traffic (DARE), which is an end-to-end reservation protocol to support QoS in MAC layer in WMNs. The protocol reserves periodically occurring time slots in the nodes in a distributed manner. It has 5 phases as followings: first, reservation setup in which time resources of nodes along the path between the source and destination pair are reserved; second, real-time data transmission; third, reservation protection in which the transmission is protected against interference; fourth, reservation repair in which the link and node failures are recovered in two steps: route repair reservation repair; fifth, reservation release in which the reservation is released when the corresponding real-time flow is finished.
- Experiment carried out: The authors implement DARE, Distributed Coordination Function (DCF), and Enhanced Distributed Channel Access (EDCA) in both real-time flow and non-real-time flows via NS-2. They compare their performance in terms of the delay of packets, the throughput for individual real-time flow and the amount of slot

shifts and block flows. Moreover, the authors evaluate the impact of background traffic, node outage, number of hops and packet size.

- Results obtained: The authors state that the results of the Cumulative Distributed Function (CDF) of delay show that with the number of offered flows increasing, the delay CDF of DARE is not as obvious as the one of DCF and EDCA. Moreover, they state that the results demonstrate that DARE gain constant delay but DCF and EDCA gain higher offered load. They claim that the results of the throughput show that DCF gain lowest throughput, EDCA performs better than DARE when the number of real-time flow is less than 10, but worse when the number of flow is more than 20. In addition, they state that the simulation results show that the delay and throughput of DARE is not changed much when the background traffic is increased, but those of DCF and EDCA are not. They also state that DARE can work better than DCF and EDCA when the topology of network changes frequently or with the number of hops increased and with the packet size increasing, its maximum number of paths does not change much.
- Conclusion: The authors claim that DARE can provide a reliable and efficient support for QoS applications.
- Papers that refer to this paper:
  This paper has 9 citations on google scholar. None of them is related to this survey.
- Future work: The authors state that they will work on the suitability of DARE in networks with mobile nodes in the future.

[Das et al. 2007]

- Previous work referred to and Problem to be resolved: The authors state that in the previous work the priorities of different flows are assigned statically based on QoS requirements. Moreover, the traditional schemes are probabilistic and cannot provide service plan effectively. By analyzing the off-the-shelf solution and the optimal scheduling solution proposed by [Salem and Hybaux 2005], the authors provide a system to addresses the problem of providing a guarantee of individual client fairness, specifically the “bitrate-for-bucks” service, dynamically based on the queue lengths.
- New system carried out: The authors propose the APOLLO system which maintains the simplicity of off-the-shelf and performs practical scheduling of packet transmission.

There are 3 parts in APOLLP as followings: first, a theory-guided service planning and subscription in which how to admit the new subscription is determined; second, a rate-based admission control in which the traffic load is enforced with the corresponding service plan; third, a distributed light-weight fair scheduling scheme in which the admitted traffic is transferred.

- Experiment carried out: The authors simulate APOLLO in two scenarios, chain topologies and large networks, by using Qualnet simulator and compare its performance with the ones of 802.11 and FS+IS in terms of throughput and average packet delay. Moreover, they implement it in the MAP testbed in the following traffic scenarios: dominant flow, balanced-flows, TCP upload, TCP download, link failure and caveat and compare the throughput of APOLLO with the one of 802.11.
- Results obtained: The authors state that the results of the implementation show that APOLLO perform well in many different network topologies and traffic scenarios and outperform 802.11 in most implementations. As for the link failure scenarios, the authors state APOLLO can deal with temporary fluctuations such as route recomputation, external interference and fading. They also claim that the results demonstrate that the throughput of the designated node under 802.11 is 62% of its service plan, while it is 93% under APOLLO system.
- Conclusion: The authors claim that APOLLP addresses a significant problem in the deployment and management of WMNs and works well in real-world scenarios.

[Dong et al. 2005]

- Previous work referred to and Problem to be resolved: The authors state that [Banerjee and Misra 2002] provided an energy efficient approach for the wireless communication. However, it is based on the link layers which are reliable. They claim that they are the first to address the problem of providing reliable and energy efficient transmission in the unreliable or lossy link layer in WMNs.
- New algorithms carried out: By assuming all of the nodes in the network have omnidirectional antennas, two centralized and one distributed algorithms are proposed, which are called Basic Algorithm for Minimum Energy Routing (BAMER), General Algorithm for Minimum Energy Routing (GAMER) and Distributed Algorithm for

Minimum Energy Routing (DAMER) respectively. All of them are for single path routing. BAMER is applied in simple end-to-end retransmission model. However, it also can be used in mixed model via a preprocessing stage. GAMER is applied in more general and realistic mixed retransmission model. DAMER is used in distributed case. In addition, DAMER can be used for single and multi-path routing.

- Experiment carried out: The authors implement DAMER, and compare them with BMA and GRAB respectively in terms of the effects of link error rates, α, hop-by-hop retransmission and network size.
- Results obtained: The authors state that the results of the simulation show that DAMER outperform BMA in the end-to-end retransmission model. Moreover, they state that the results show that minimum energy paths can be found via DAMER in the hop-by-hop retransmission model. They also claim that the results of the effect of network size show that with the network size increasing, the energy efficiency of BMA is lower. However, the proposed algorithms can handle this problem.
- Conclusion: The authors state that the proposed algorithms can provide reliable transmission in the WMNs by using minimum energy. They also claim that DAMER performs better than BAMER, GAMER and the existing single or multiple-path approaches.
- Papers that refer to this paper:

  This paper has 30 citations on google scholar. Only one is related to this survey which is as the following:

  AKYILDIZ, I.F., WANG, W., AND WAN, X. 2005. Wireless Mesh Networks: A Survey. *Computer Networks*, 47(4), 445-487.

[Hsiao and Kung 2005]

- Previous work referred to: The authors state that previous routing protocols do not perform well in terms of the routing message overhead and end-to-end control delay in the wireless networks. Though some approaches are proposed to overcome the above-mentioned problems, such as the algorithms proposed by [Park and Corson 1997], [Nasipuri et al. 2001] and [Ganesan et al. 2001], they are complicated and difficult to deal with.

- Problem to be resolved: This paper provides an approach to provide not only a simultaneously usable, but also a fail-safe wireless networks infrastructure.
- New algorithm carried out: By assuming that all of the positions of APs are known, the authors propose a new mesh construction algorithm called "beam-crossing grids", in which the networks are cut into several square regions to form the multiple but not interfering wireless meshes. It provides redundancy at the link level for the failures. When there is a failure in the current wireless mesh network, the directional antennas of APs controlled by the software can access another backup network. If there are no failures, the multiple mesh networks will work in parallel to expand the bandwidth of the networks. The authors also provide an upper bound on the running time of the proposed algorithm.
- Experiment carried out: In this paper, the authors implement two collocated wireless networks in which the APs are placed randomly and connected via tree topologies. They implement the simulations in seven conditions with different densities and then analysis the results in terms of coverage ratio and the number of APs used. In addition, they state that the algorithm works when there are more than two collocated wireless networks.
- Results obtained: The authors state that the results of coverage ratios show that the proposed algorithm is effective to searching for two networks without influencing the current coverage. It increases when the density or access radio range increases. They also claim that the results of the number of APs used show that twice as many APs should be supported to the algorithm than those would be used to gain good performance. In other words, the density must be equal to or greater than eight. The authors also state that the proposed approach can be used not only for the purpose of increasing the total throughput of the wireless mesh network, but also for deploying the APs.
- Conclusion: The authors claim that two wireless mesh networks can work in parallel without interfering with each other by using beam-crossing grids algorithm. In addition, they state that the terminal nodes can use it for fault-tolerance or load balancing purpose.
- Future work: The authors state that they will do the following work in the future: first, consider the AP coverage patterns; second, extend the approach to three collocated wireless networks; finally, investigate the application by considering that APs can adjust their transmitting power level.

[Kim et al. 2007]

- Problem to be resolved and Previous work referred to: This paper addresses four important problems in the previous channel-related research of WMNs, which are as the followings: first, overhead is high and scalability is limit when implementing the existing network configuration algorithms; second, it is unavailable to obtain accurate information in dynamic networks; third, the recovery from the failure may cause other QoS failures when applying the greedy algorithm [Raniwala and Chiueh 2007]; finally, some fault-tolerance routing protocols such as local re-routing [Nelakuditi et al. 2005] and multi-path routing [Chen et al. 1999] require more resources compared with the reconfiguration.
- New algorithm carried out: The authors propose an algorithm called Localized sElf-reconfiGuration algorithms (LEGO), in which there are three main parts: monitoring, reconfiguration and planning, to make the multi-radio of WMN to recover from the local link failures.
- Experiment carried out: LEGO is implemented in the indoor multi-radio WMN with the Linux-based system. The authors evaluate LEGO in two aspects: the channel efficiency gained and the avoidance of ripple effects. In addition, the authors implement the local re-routing, static channel-assignment algorithm and greedy algorithm and then compare the experiment results of these recovery approaches.
- Results obtained: The authors state that the channel efficiency gained by LEGO and greedy algorithm are the same and better than the one of the other two. They also indicate that as for the avoidance of ripple effects, the throughput LEGO achieves is nearly the optimal throughput, while local re-routing gains only 82% of the optimal one and the static channel-assignment algorithm perform the worst of all.
- Conclusion: The authors claim that the improvement of LEGO in channel efficiency is up to 92% and it is effective to avoid the ripple effects.
- Future work: The authors states that they will optimize both channel and flow assignments, and the measure the link failure characterization in multi-radio WMNs.

[Lee and Ward 2004]

- Previous work referred to: The authors state that though the traditional routing algorithms such as DSR and AOVD can be implemented in WMNs, the performance is not the best because some assumptions are not true in WMNs.
- Problem to be resolved: This paper provides an algorithm to address the problem of load-balancing and fault tolerance in WMNs.
- New protocol carried out: The author claim that packet delay in WMNs can be minimized by using shortest path, however, the collisions should be taken into account at the same time. Hence, they propose a shortest-path load-balancing diverse routing protocol by utilizing quasi-xy-routing algorithm. There are four steps in the protocol as the followings: if the next hop is gateway, compete for transmission with it; determine neighbors' load; select a lightly-loaded path; go to the step 1. Moreover, the authors introduce a theorem to determine the number of available path.
- Analysis carried out: The authors state that the common failures are caused by power-off or system failure in WMNs. By using the proposed protocol, they claim that the protocol can choose another diverse path to recover the link failure. They also state that when a node's, called island node, entire neighbor nodes do not work, it can increase its power to communicate with the farther neighbors. However, the authors state that some island nodes restore their power until there are new nodes. The authors also study the effect of gateway on the performance of the protocol. By the assuming that nodes can use more than one gateway and the positions of the gateways can affect the throughput of the network, the authors state that adding gateway can relieve the traffic congestion when the existing ones cannot deal with more traffic. Moreover, they claim that the throughput of load-balanced network increases with the increment of the number of gateways linearly.
- Conclusion: The authors claim that the proposed protocol can provide robustness and outperform the traditional ad hoc routing protocols.
- Papers that refer to this paper:

  This paper has 2 citations on google scholar. None of them is related to this survey.
- Future work: The authors state that they will do the following work in the future: first, integrate routing and scheduling algorithms and study the performance of WMNs; second, study on the number and the placement of the gateway used in the network; third, work

on the traffic model of wireless shortest-path load-balancing diverse routing protocol by utilizing quasi-xy-routing algorithm s network.

[Lumetta and Medard 2001]

- Previous work referred to and Problem to be resolved: The authors state that it is critical to make sure that the recovery from a failure does not affect the ability of the whole network and multiple failures should be considered in failure localization. However, most existing recovery algorithms only consider a single link or node failure. Hence, a quantitative measure of a network's ability to recover from two-link failure is proposed by investigating the relationship between failure localization and the properties of link restoration algorithms.
- New algorithm and scheme carried out: The authors propose a genetic algorithm which uses the concepts in biological evolution to search path. The genetic algorithm begins at the creation of a random initial population of candidate digraphs, and then the iterative refinement process is proceeded to create the next generation. A "fitness" value is calculated as the weight in the selection process and it affects the search path heavily. The authors also present a classification scheme for two-link failures which can be sorted into three types: fundamental failures, basic algorithmic failures and practical algorithmic failures. The three classes are integrated into a dependence hierarchy.
- Experiment carried out: The authors implement the classification scheme to three networks: national network, New Jersey LATA network and ARPANET and compare performance in terms of vulnerability by varying the distribution and number of failures in the network.
- Results obtained: The authors state that the results demonstrate that the vulnerability increases from NJLATA, to national and Arpanet. In addition, they state that the implementation results show that the use of double cycle cover induced between 20 and 70% higher vulnerability than did the use of preplanned shortest paths. They also state that based on the average node degree of the network, the gap between the latter and generalized loopback is changed between 20 and 55%. Moreover, they claim that the results show that the difference between the limits imposed by the network topology and generalized loopback ranged from 86 to 213%.

- Conclusion: The authors claim that the proposed scheme can recover from most types of the mentioned failures.
- Papers that refer to this paper:

  This paper has 32 citations on google scholar. Only one is related to this survey which is as the following:

  WU, Y., HUI, J. AND SUN, H. 2003. Fast Restoring Gigabit Wireless Networks Using a Directional Mesh Architecture. *Computer Communication*. 26(17), 1957-1964.
- Future work: The authors state that they will do the following research in the future: first, investigate the approaches of addressing the problem of path hit by using pre-encoding or other ways; second, work on the strategies for switching existing connection from the loss links due to a failure to protected links; third, investigate the interaction between link restoration and the recovery algorithms.

[Mir et al. 2008]

- Previous work referred to and Problem to be resolved: The authors state that the existing ad hoc routing protocols, such as AODV, do not perform well in Hybrid WMNs which is a combination of static mesh routers and mobile mesh clients. They state that the AODV cannot distinguish between the two kinds of node mentioned, minimize co-channel interference and maximize the use of multiple orthogonal channels between the source-destination pair. Hence, based on AODV, the authors provide a new protocol to address those problems which improves the performance of packet delivery and latency in Hybrid WMNs.
- New protocol carried out: The authors propose a modified AODV routing protocol called Hybrid On-demand Distance Vector Routing (HOVER). HOVER has the same route discovery mechanism as AODV-MR, however, in order to establish router, provide optimal link selection, it adds 3 new mechanisms as the followings: node-type aware routing, link quality estimation and optimal link selection. The authors state that HOVER establishes a path between a pair of nodes quickly to minimize the path creation delay and changes it when it finds a better path. When an invalidated link is detected on the active route, HOVER will switch the route to use another valid link locally.

- Experiment carried out: The authors implement HOVER in NS-2 by using Extended Network Simulator extensions. They evaluate the performance of HOVER by changing mesh client speeds and traffic load in terms of aggregate goodput, average latency and routing packet overhead and compare them with those of AODV-MR. Moreover, they implement a prototype of HOVER in a testbed.
- Results obtained: By varying the mesh client speeds, the authors state that the experimental results show that HOVER gain higher goodput and more number of control packets than AODV-MR, it cost less packet delay since it can forward packets with less contention and interference. By varying the traffic load, the authors state that the implementation results show that HOVER still achieves higher goodput than AODV-MR. They also state that the results show that when the number of flow is 10, the delivery ratio of HOVER and AODV-MR are nearly 100%, however, when the number of flow is 20 or 30, the delivery ratio of HOVER gain 25% improvement. The authors claim that the simulation results show that the latency of packet of HOVER is more than 100ms lower than that of AODV-MR and the overhead of HOVER is lower than the one of AODV-MR when the number of flow less than 40. Moreover, the authors state that HOVER improve the latency of AODV-MR, however, they claim that the improvement in latency is obvious higher in the testbed than in the simulation results.
- Conclusion: The authors claim that HOVER outperforms AODV-MR in terms of packet delivery and latency in Hybrid WMNs.

[Nelakuditi et al. 2005]

- Problem to be resolved and previous work referred to: This paper addresses two issues: first, scalability of the traditional routing schemes for WMNs is poor; second, though the previous routing approaches, such as FSR [Gerla et al. 2002], HSLS [Santivanez et al. 2001], failure insensitive routing approach [Lee et al. 2004] and an algorithm proposed by [Narvaez et al. 1999], perform well when one link failure happen; it is hard for them to recover from two or more link failures. There is a scheme proposed in this paper which can ensure loop-free delivery without requiring the accurate information of the networks. In addition, this paper states the greedy forwarding approach, and compares it with the proposed scheme.

- New approach carried out: The authors propose a link-state-based blacklist-aided forwarding (BAF) approach, in which the packet is forwarded in greedy mode and recovery mode. This approach takes advantage of the fact that the nodes are static in WMNs and balance the trade-offs of its reliability, optimality and scalability. Based on BAF, the authors also propose the other two routing schemes called blacklist-aided forwarding with learning (BAFL) and fine-grain blacklist-aided forwarding (FBAF).
- Experiment carried out: The authors first generate 200 nodes in a field, none of which are too close to each other. They implement BAF, BAFL and FBAF in the environment mentioned above. They also analyze the experiment results via three aspects: reliability, optimality and scalability.
- Results obtained: The authors claim that the performance of BAF and BAFL are only different in terms of optimality. The authors gain the following conclusions from the experimental results: first, the results show that BAF can handle multiple link and node failures without updating the whole link information. It can make the routing reliable even in some severe condition; second, optimality also can be controlled. BAF can trade off the optimality and scalability without changing its reliability; finally, BAF is a scalable scheme because its overhead of communication and computation are small.
- Conclusion: The authors conclude that BAF is reliable, highly-scalable and near-optimal.
- Papers that refer to this paper:

  This paper has 7 citations on google scholar. Only one is related to this survey which is as the following:

  KIM , KYU-HAN AND SHIN, KANG G. 2007. Self-Healing Multi-Radio Wireless Mesh Networks. *Proceedings of the 13th annual ACM international conference on Mobile computing and networking.* 326-329

- Future work: The authors state that they are implementing schemes such as LASR [Draves et al.2001] and HSLS [Santivanez et al. 2001] via NS2 and will compare the their performance with BAF. In addition, they will implement real-world experiments of BAF.

[Pirzada et al. 2007]

- Previous work referred to: The authors claim that there is no previous work. They are the first one to do this research. However, the proposed routing protocol is an extension of the Ad-hoc On-demand Distance Vector (AODV) routing protocol. The original AODV is used for single-radio nodes and the modified one called AODV-MR can support the multi-radio nodes. In this paper, AODV-MR is referred.
- Problem to be resolved: This paper addresses the problem of discovering and exploiting multiple bidirectional links between a node and its neighbor nodes in WMNs.
- New protocol carried out: The authors propose a protocol which is an extension of AODV called AODV-ML. in which two stages are used to discover multiple links: one is route establishment process of the protocol, the other one is the communication between nodes. The authors state that, by using the proposed protocol, the source node can create a single bidirectional link with its neighbor node and the other ones can create multiple links to their immediate adjacent nodes. They also state that the additional links can be used for the applications such as the followings: link repairing, link optimization, load-balancing and striping.
- Experiment carried out: By considering the WMN is hybrid and making five assumptions, the authors implemented AODV-MR in terms of link optimization and repairing with Mesh Client speeds and traffic loads changing. They analysis its performance in the following three metrics: packet delivery ratio, routing packet overhead and average latency and then compare them with those of AODV-MR.
- Results obtained: The authors state that the results of PDR show that when the Mesh Client speed is from 0 to 20m/s, the packet delivery ratio of AODV-ML is decreased from 100% to 94% and the one of AODV-MR is from 55% to 43%. However, the authors claim that AODV-ML have more than 100% improvement over AODV-MR when the time of connection is over 20. They also claim that the results of routing overhead show that the one of AODV-MR increase to ten control packets for one data packet, however, the one of AODV-ML is fewer than 2. They state that when the number of connections increasing, the routing overhead of AODV-MR increase obviously but AODV-ML can handle this condition. The authors also state that the results of average latency show that delay increase distinct by using AODV-MR, but it is not by using AODV-ML.

- Conclusion: The authors claim that the proposed protocol outperforms AODV-MR and can be utilized in a wide range of WMNs.

[Raman and Chebrolu 2005]

- Previous work referred to and Problem to be resolved: The authors state that the 802.11 CSMA/CA MAC can handle with the contention in indoor cases, however, it is not efficient in WMNs, especially the ones with long-distance links. Though some technologies can be used in CSMA/CA to alleviate its inefficiency, they have a high cost. Hence, the authors present a new protocol based on SynTx/SynRx proposed by [Raman and Chebrolu 2004]. It not only improves the performance of 802.11 but also retain the cost advantages of 802.11.
- New protocol carried out: The authors propose a new MAC protocol called 2P which is an alternative to the 802.11 CSMA/CA. 2P operates on the link by making all interfaces coordinate their switch between SynRx and SynTc in which the temporary loss of synchrony and recovery from a link failure are resolved. A timeout mechanism which works only there is a link failure or complete packet loss is introduced in 2P. The authors also present two dependences of 2P which are as followings: the bipartite topology and the feasibility of SynOp at all nodes and the related set of SINR equations for all the interfaces. Moreover, the authors propose a heuristic to create a tree topology in which the 2P can be used. There are seven steps in the heuristic and it will execute until all nodes are connected or a link failure is detected.
- Experiment carried out: The authors simulate 2P in the ns-2. They also implement the CSMA/CA and compare its performance with 2P in terms of saturation throughput and TCP performance. Moreover, they evaluate 2P in the prototype implementation in three stages as the followings: confirmation of SynOp with Prism2 cards, performance on a single link and on a pair of links.
- Results obtained: The authors state that the simulation results show that the bandwidth of nodes in 2P scenario is at least 3-4 times more than the one in the CSMA/CA. They also state that the results of TCP throughput for the cases of loss free demonstrate that compare with CSMA/CA, 8-20 fold improvement in throughput are gained in 2P scenario. Moreover, they claim that the results show that when LLC cannot recover from the

packet loss, the performance of uniform and bursty losses is similar to the no loss case. In addition, the authors claim that the simulation results show 2P can operate all the links simultaneously without mutual interference and gain good robustness against losses by using minimal overhead. They also claim that the performance of 2P is 20 times better than the one of CSMA/CA and close to optimal performance when having all the links working at all time.

- Conclusion: The authors claim that by using a single channel 2P gains maximal efficiency without requiring tight time synchronization and it performs obvious improvement compared with CSMA/CA in long-distance mesh networks. Moreover, they state that 2P is available in the network topologies design.
- Papers that refer to this paper:

  This paper has 69 citations on google scholar. Only one is related to this survey which is as the following:

  PIRZADA, A., WISHART, R., AND PORTMANN, M. 2007. Multi-Linked AODV Routing Protocol for Wireless Mesh Networks. *Global Telecommunications Conference, 2007. GLOBECOM '07. IEEE***.** 4925-4930.

[Tabata et al. 2003]

- Previous work referred to: The authors state that it is critical that every node shares the same time in the networks. They state that GPS is proposed to resolve this problem. However, it can be only used indoors. They also claim that [Young 1998] and [Kabata et al. 2001] present approaches to establish network-wide synchronization, in which a master node is needed, but these approaches cannot handle the failure of master nodes. They state that [Wang and Nakagawa 1998] introduce a scheme with the assumption that all the nodes can detect synchronous pulse from each other. However, it does not work when the nodes are distributed over a wide range of areas or use directional antennas.
- Problem to be resolved: This paper address of the problem of providing the synchronization without centralized control and recovering from link failures in WMNs.
- New scheme carried out: The authors propose a scheme to establish synchronization autonomously without centralized control in wireless networks. It can work with the information from the adjacent nodes and can recover the link or node failure happened in

local area. There are 4 phases in the scheme: first, clock sync in which synchronization between two clocks is built at each node; second, cancel subordination which is the critical phase and is executed by all nodes; third, change superordinate clock which is used to maintain synchronization; fourth, change priority. Three kinds of messages are used as followings: SYNC REQUEST, SYNC END and CHANGE PRIORITY. The authors also present a concept of link priority in the scheme to avoid synchronous loop.

- Example carried out: The authors give an example of the proposed scheme, in which there are 11 nodes with given priority and 12 links. They use them to present the procedure of establishing network synchronization in detail. Moreover, they show the procedure of recovering from the link failure for synchronization.
- Conclusion: The author claim that the proposed scheme can establish synchronization and recover from link failure. They also state that it can be used in the network whose topology is changed frequently.
- Papers that refer to this paper:
  This paper has 9 citations on google scholar. None of them is related to this survey.

[Tsai and Moors 2007]

- Previous work referred to: Previous metrics focus on the use of additional data redundancy to gain better delivery rate by using non-disjoint paths, such as the single path WCETT metric [Draves et al. 2004], a maximally disjoint (MD) path selection metric and the CAM metric [Sheriff et al. 2006].
- Problem to be resolved: This paper addresses the problem of providing reliability routing in multi-radio, multi-channel wireless mesh network by selecting multiple routing paths.
- New metric carried out: The authors propose a new interference-aware multipath selection metric name Weighted Interference Multipath (WIM), which is based on the ETT metric and interference minimisation. It uses different concurrent paths to transmit the duplications of data to improve the end-to-end reliability and gain low delay.
- Experiment carried out: The authors use Optimized Link State Routing protocol as the link-state exchange framework and NS2 v2.30 as the simulator. They simulate the WCETT, MD, CAM and WIM metrics and compare their performance in terms of path length between the source node and destination node, the degree of spatial diversity of

the path selected and the resilience to localized failures it can provide, the packet loss reduced by the various degrees of the link layer retransmissions.

- Results obtained: The authors state that they obtain the following results via the experiment: first, the selected paths provide the highest delivery ratios with slightly higher delays via WIM, but provide lower delivery ratios with lower delays; second, the spatial diversity is correlated to resilience against failures happen in local networks; third, the separation of paths selected is smaller via CAM than via the other metrics; finally, with two retransmissions, WIM achieve relative 0.95 delivery ratio and 0.15 delays which are better than the other metric in the same condition.
- Conclusion: The authors claim that WIM provides higher reliability and lower delay than MD path selection and CAM.
- Future work: The authors state that they will do the following work in future: first, find a more feasible way to select path; second, use erasure code to provide the data redundancy; finally, find a more realistic and accurate approach to categorize the interference between nodes.

[Wu et al. 2003]

- Previous work referred to: The authors state that the distributed pre-planned techniques cannot handle all cases of multiple failures since they only have local knowledge but not global knowledge.
- Problem to be resolved: This paper addresses the problem of detecting and restoring transient node and link failures in directional WMNs.
- New scheme carried out: The authors propose a restoration scheme called Hybrid Fast Restoration Scheme (HFRS) in which local and global restorations are used. Its main idea is the recovery strategy called local recovery for local failure. There are two phases in this scheme: one is route pre-planning phases in which path is generated; the other one is real-time phase in which failures are recovered.
- Experiment carried out: The authors implement HFRS in two network models: typical mesh network and New Jersey LATA. They also estimated its performance during the recovery of single link failure, multiple links failure and single node failure in terms of

recovery time, probability of algorithm failure, in which five failure conditions are tested, and average end-to-end blocking probability.

- Results obtained: The authors state that the results of recovery time show that it is not increased much with average link usage increasing. They also claim that results of average end-to-end blocking probability show that all the single link failure and 95% double link failures are corrected. They state that the results show that blocking probability increase when the number of link failures increase. They also state that 95% single-node failure can be recovered. Moreover, the authors claim the results of probability of algorithm failure show that HFRS gain 97.5% efficiency of restoration in typical mesh network model and 98% in New Jersey LATA.
- Conclusion: The authors claim that the HFRS can recover single link, multiple links and single node failure. Moreover, they state that HFRS is distributed and scalable.

[Yuan et al. 2005]

- Previous work referred to: Forwarding meshes were used by [Lee et al. 2000], [Chiang and Gerla 1998], and [Garcia-luna-Aceves and Madruga 1999] to increase the robust multicast delivery in ad hoc networks. They require the intermediate nodes provide accurate information of their position. Though [Zhong et al. 2005] constructs a forwarding mesh on the fly to improve the scaling and robust of the protocol, its overhead is significant and it is implemented in the sensor networks. In addition, it does not optimize the transient throughout. Biswas and Morris have provided the concept of opportunistic routing for wireless mesh networks in 2002 and 2005, which exploits the independent reception of transmissions at different nodes. However, it does not leverage the multi-rate option explicitly and address the problem of resilience. [Banerjee et al. 2002] have proposed the randomized forwarding which focuses on resilience for wired multicast networks.
- Problem to be resolved: This paper addresses the two problems: the resilience against lossy wireless links, channel outages and node failures and the high throughput routing. It balances the long term rout optimality and the short term opportunistic performance.
- New protocol carried out: The authors describe ROMER, a resilient and opportunistic routing protocol for wireless mesh networks. Its main idea is to use credit mechanism to

build a path between the source node and destination node. There are two parts in ROMER: one is runtime candidate mesh, in which the mesh is formed on the fly for each packet and the width of the mesh can by adjust readily. The other one is randomized opportunistic forwarding, in which the transient transmission rate variations can be leveraged.

- Analysis carried out: The authors analyze the opportunistic throughput gain and the robustness of ROMER. They state that ROMER can deliver near-optimal throughput in the network layer and gain a constant end-to-end delivery ratio.
- Experiment carried out: The authors simulate ROMER by using ns-2. They also implement single-path distance-vector routing algorithm and 2-disjoint-path routing and compare their performance with ROMER in terms of throughput gain and resilience against lossy links and node outages.
- Results obtained: The authors state that the experimental results show that ROMER provide higher throughput gain than single-path algorithm and it provide higher delivery ratio than both single-path algorithm and 2-disjoint-path routing.
- Conclusion: The authors claim that ROMER can provide robustness against transient/persistent link failure and node outages, and maximize the end-to-end throughput.
- Papers that refer to this paper:

  This paper has 13 citations on google scholar. Only one is related to this survey which is as the following:

  ZHAO, X., CHOU, C.T., GUO, J., AND JHA, S. 2006. Protecting Multicast Sessions in Wireless Mesh Networks. *Local Computer Networks, Proceeding 2006 31st IEEE Conference on*. 467-474.

- Future work: The authors state that they will do the following three things on ROMER in future: first, refine the analysis; second, enhance its resilience against the malicious attacks; finally, add mobility support to deal with the client mobility.

[Zhao et al. 2006]

- Previous work referred to: The authors claim that there is no precious work on the issue of protecting multicast sessions. Hence, they are the first to do this research.

- Problem to be resolved: This paper addresses the problem of protecting multicast sessions in wireless mesh networks.
- New approach and algorithms carried out: The authors propose a resilient forwarding approach called resilience forwarding mesh (RFM) to protect the multicast sessions against the link or node failure in WMNs. It builds two node-disjoint paths between the source-destination pair by using the advantage of wireless broadcast in which it uses the least number of required broadcast nodes. The authors state that to find the solution of this problem is NP-complete. Hence, they propose four heuristic algorithms called node-disjoint tree algorithm (NDT), revised node-disjoint tree algorithm (RNDT), shared disjoint mesh algorithm (SDM) and minimal disjoint mesh algorithm (MDM) to find the approximate solutions of RFM.
- Experiment carried out: The authors deploy 28 nodes in the networks and choose one-M nodes randomly as the source-destination pair. They implement the four heuristic mentioned above and the ORFM, the solution of RFM obtained by using CLPEX. Besides, the authors implement the single multicast tree proposed by [Ruiz and Gomez-Skarmeta 2005] and the optimal non-protected tree, and then compare the performance of them in terms of the number of the broadcast nodes and the overhead.
- Results obtained: The authors state that the experimental results show that the performance of MDM is close to the one of ORFM, and the others from best to worst are SDM, RNDT and NDT. Moreover, they state that the biggest gap between MDM and ORFM is less than 2 nodes when the size of multicast session is 10. They also state that the results of overhead show that the overhead of MDM is nearly twice of Ruiz's tree when the size of session is small, however, as the number of session is increasing, the overhead of MDM does not increase much. They state that when the size of session is large, MDM needs about 5 more broadcast nodes, which is less than one third more broadcast nodes than Ruiz's tree.
- Conclusion: The authors claim that RFM can provide efficient 1+1 protection to the multicast session without bringing in much additional overhead compared with a single multicast tree. They also state that MDM perform the best and is close to the ORFM.
- Papers that refer to this paper:

This paper has 3 citations on google scholar. Only one is related to this survey which is as the following:

ZHAO, X., CHOU, C.T., GUO, J., AND JHA, S. 2007. A Scheme for Probabilistically Reliable Mutilcast Routing in Wireless Mesh Networks. *Local Computer Networks, 2007. LCN 2007. 32nd IEEE Conference on.* 213-214.

- Future work: The authors state that they will work on searching for RMF in a distributed scheme.

[Zhao et al. 2007]

- Previous work referred to: [Zhao et al. 2006] proposed a Resilient Forwarding Mesh (RFM) approach to protect multicast sessions from the failures in WMNs, in which the authors build two node-disjoint paths for a source-destination pair.
- Problem to be resolved: This paper addresses the problem of finding probability reliable paths for multicast in wireless mesh networks.
- New scheme carried out: The authors propose a scheme called Probabilistically Reliable Multicast Routing (PRMR) to enhance the reliability of multicast routing, in which a directional link packet delivery rate is used as the metric to choose the forwarding nodes and two disjoint paths are established for a source-destination pair. Moreover, the authors propose an algorithm for PRMR.
- Experiment carried out: The authors simulate PRMR via Qualnet. In the simulation, the source node sends multicast constant bit rate traffic and interference traffic is sent in random constant bit rate. They also implement ODMRP proposed by [Lee et al. 2003] and compare their performance in terms of average reliability, lowest reliability and overhead. The authors simulate the multicast sessions with 7 different sizes, and 10 topologies for each size.
- Results obtained: The authors state that the results show that the performance of PRMR is always better than ODMRP. PRMR gain 25% more of the average reliability and 50% more of the lowest reliability than ODMRP. They claim that PRMR needs over 50% more broadcast nodes than ODMRP when the session size is small. However, when the session size is large, they claim that PRMR only needs nearly 2 more broadcast nodes

than ODMRP and gain more than 20% improvement in both average reliability and lowest reliability.

- Conclusion: The authors claim that PRMR can enhance the reliability of multicast routing in WMNs.

[Zeng and Zeng 2007]

- Previous work referred to: The authors state that the traditional architecture of single channel wireless network cannot support the applications with bandwidth requirement sufficiently. Hence, they utilize multiple channels to make the throughput of network larger. They state that the proposed distributed algorithm used in scheduling scheme is based on the one proposed by [Kumar et al. 2005].
- Problem to be resolved: This paper addresses the problem of interference aware bandwidth guaranteed scheduling and the problem of shortest path routing in multi-channel WMNs.
- New scheme and algorithm carried out: By analyzing the necessary and sufficient conditions for link flow scheduling, the authors proposed the bandwidth guaranteed shortest path scheduling in which a distributed algorithm and a TDMA is used. In the algorithm, slots are assigned to every edge according to the bandwidth requirement. In addition, the authors present a routing algorithm based on the k-shortest path. There are three stages in the routing process as the followings: first, route discovery in which routes without enough bandwidth for the flow are removed via partial admission control; second, route reply; third, route maintenance in which link failure can be recovered.
- Experiment carried out: The authors implement BGSR with k=1 and k=4 for the bandwidth guaranteed k-shortest path respectively. They also simulate minimum hop-count (shortest) path touting algorithm (MSP) and compare its performance with BGSR in terms of connection request blocking ratio. In the simulation, five parameters which influence the performance are varied.
- Results obtained: The authors state that the results show that BGSR perform better than MSP and BGSR with k=4 outperform the one with k=1. They also state that the results show that with the maximal bandwidth requirement increased, block ratio is increased, but it is decreased when more channels and capacity is available in the network.

Moreover, they claim that the results of the simulation show that block ratio will not be cut down when increase the Network Interface Cards (NICs).

- Conclusion: The authors claim that the proposed algorithm outperforms MSP and can provide efficient bandwidth guaranteed path for connection request with lower blocking ratio.
- Future work: The authors state that they will do research on multicast routing for bandwidth guaranteed scheduling and routing problems. Moreover, they claim that they will work on distributed algorithm on multicast routing.