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Routing protocols in wireless mesh networks: challenges and design considerations

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Abstract Wireless Mesh Networks (WMNs) are an emerging technology that could revolutionize the way wireless network access is provided. The interconnection of access points using wireless links exhibits great potential in addressing the "last mile" connectivity issue. To realize this vision, it is imperative to provide efficient resource management. Resource management encompasses a number of different issues, including routing. Although a profusion of routing mechanisms has been proposed for other wireless networks, the unique characteristics of WMNs (e.g., wireless backbone) suggest that WMNs demand a specific solution. To have a clear and precise focus on future research in WMN routing, the characteristics of WMNs that have a strong impact on routing must be identified. Then a set of criteria is defined against which the existing routing protocols from ad hoc, sensor, and WMNs can be evaluated and performance metrics identified. This will serve as the basis for deriving the key design features for routing in wireless mesh networks. Thus, this paper will help to guide and refocus future works in this area.

Keywords Wireless mesh networks · Routing

1 Introduction

Extending high-speed IP connectivity to the "last mile" is an open and on-going research problem with no satisfactory solution. A number of potential solutions have been proposed, including full end-to-end optical networks and wireless access networks. However, deploying these networks requires the installation of a large amount of wire/fibre. The initial investment costs for deployment, and the difficulty

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of deployment in some environment settings (established urban areas, wilderness, etc.), have prevented the widespread realization of such access networks.

Wireless Mesh Networks (WMNs), consisting of wireless access networks interconnected by a wireless backbone, present an attractive alternative. Compared to optical networks, WMNs have low investment overhead and can be rapidly deployed. The wireless infrastructure is self-organizing, self-optimizing, and fault tolerant. It can extend IP connectivity to regions otherwise unreachable by any single access technology. Many companies, such as Nokia [34], Microsoft [29], Motorola [31] and Intel [18], are actively promoting wireless mesh networks as a full IP solution. Initial field tests [44, 45, 50] have demonstrated WMN's tremendous potential and market value. WMNs combine concepts from a diverse set of existing and emerging wireless technologies, including cellular technologies, ad hoc networks, and sensor networks. The application of research results from these areas could greatly contribute to the development, implementation, and growth of wireless mesh networks.

However, the lack of a clear understanding of wireless mesh network characteristics and the absence of targeted resource management and service provisioning mechanisms can jeopardize their successful development. Issues inherent to Wireless Mesh Networks require new research innovations. Moreover, it is crucial to realize that such mechanisms should cope with consumers' increasing demands for QoS guarantees.

Delivering on QoS guarantees requires a strong resource management framework, starting with an effective routing protocol. The multi-hop wireless nature of a WMN demands a different approach to routing from conventional wireless access networks. It has much more in common with the ad hoc and sensor network fields. However, the overall properties of the individual nodes and the overall network are very different in many ways. Therefore, it is unclear exactly how applicable these approaches are to a WMN.

This paper addresses the issue of routing in a WMN, by considering the specific characteristics of a WMN. It explores existing solutions, and evaluates their suitability to the wireless mesh environment. Based on this evaluation, the need for developing new routing mechanisms, specifically tailored for the unique characteristics of WMNs is assessed. A number of issues and considerations are identified and presented, in order to guide future work and the development of a WMN routing protocol.

The remainder of the paper is organized as follows. Section 2 provides a general overview of wireless mesh networks and the associated resource management issues. Section 3 identifies the characteristics of wireless mesh networks. Routing issues are discussed in Section 4. Section 5 concludes this work.

2 Wireless mesh networks

2.1 Wireless mesh network: architectural view

1) *What is a wireless mesh network?*: Formally, a network topology can be abstracted by a graph $G(V, E)$ where V is the set of vertices representing the network nodes, and E is the set of edges representing the communication links between the vertices. In wireless environments, a mesh network is referred to as a connected graph such that for each $i, j \in V$, $i \neq j$, there exists a path (subset of

edges) connecting i and j. This can be further extended to k-connected graphs if path redundancy is considered. However, this strict definition fails to consider the different characteristics of the nodes and edges forming the network.

Industry has adopted different views on the concept of a mesh network. The proposals differ most significantly in the following areas:

- Network components: The role of mobile nodes as part of the wireless mesh network architecture differentiates current proposals. MIT Roofnet [30] and Nortel Networks' solutions [35] do not consider mobile nodes as part of their network infrastructure (i.e., only access points and network gateways are included). On the other hand, MeshNetworks architecture [28] considers meshing between access points, as well as between mobile nodes.
- Degrees of mobility: Some early work in WMNs [46] drew parallels between ad hoc networks and mesh networks. However, current works tend to discriminate these two network environments by considering that mesh networks are formed by a wireless backbone of non-energy constrained nodes with low (or no) mobility [9] whereas in some wireless multi-hop networks, such as MANETs, energy conservation and user mobility are the primary research focus. This shift of research concerns leads to the questioning of the suitability of applying existing ad hoc networking protocols to wireless mesh networks.
- Traffic pattern: Wireless mesh networks exhibit unique traffic patterns, which partially resemble ad hoc networks' and sensor networks'. Similar to sensor networks, data traffic is mainly expected to flow between users (sensor nodes) and the network gateway(s) (destination station or sink). This constitutes the main differentiator between wireless mesh networks and ad hoc networks in some literature, such as in [20]. However, in a WMN, traffic can also flow between any pair of user nodes (as in ad hoc networks).

To form a common understanding on what a wireless mesh network is, the following definition is presented, that is general enough to encompass most current mesh network architectures:

Definition A wireless mesh network is a packet-switched network with a static wireless backbone.

Therefore,

- The wireless backbone topology is fixed and does not have to cope with access point mobility. Modifications to infrastructure can only result from the addition/removal or failure of access points.
- Pure ad hoc networks are not considered as wireless mesh networks.

2) *Our view of the wireless mesh network architecture*: Contrary to [51], which regards a mesh network as composed of only two different entities, the mobile nodes and the access points, a more general view of a mesh network is adopted (similar to [35]). The mesh network architecture is composed of three different network elements: network gateways, access points and mobile nodes (figure 1).

- Network Gateway: This network element allows access to the wired infrastructure, possibly the Internet or other local networks. More than one gateway can be deployed in a wireless mesh network.

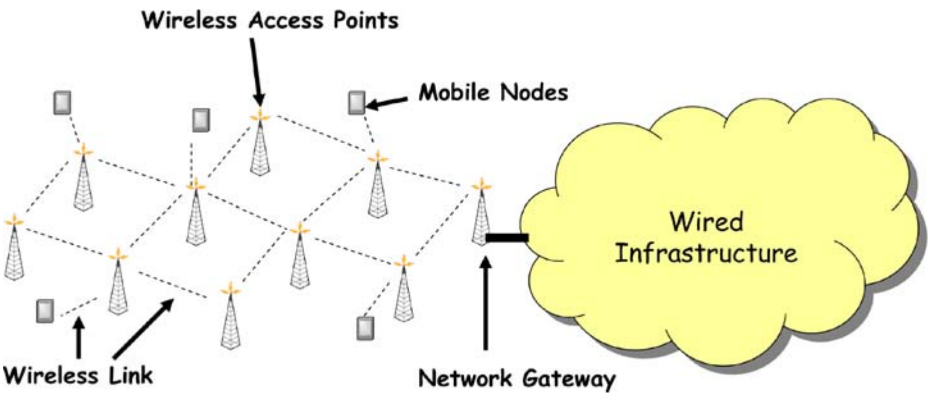

Fig. 1 Example of wireless mesh network topology

- Access Points (APs): Low cost, flexible, and easy to deploy, the APs form the network backbone spanning over wide areas. They can be embedded with enhanced capabilities (directional antennas, multiple antennas, multiple interface cards, etc.). Users connect to the APs, using wireless or wired means. The APs are assumed to be static, with a low failure probability, and no power constraints. This mesh of APs serves as a relay between the mobile terminals and the network gateways.
- Mobile Nodes[1]: They include a wide range of devices, like PDAs, laptops or cell phones, with varying degrees of mobility. Mobile nodes can significantly differ in terms of energy autonomy, computation and transmission capabilities. They communicate with the wired infrastructure by directly contacting the network gateway (according to their position and transmission capabilities) or by using the APs as relays.

In a wireless mesh network, it is not necessary for all APs to have direct connection to the network gateways. The APs may need to forward their traffic through other APs in order to reach a gateway. Access to the gateway could be further extended if we envision a mesh topology formed between the mobile nodes. The mobile nodes may be highly mobile, as in the case of a dynamic network topology (ad hoc-like).

2.2 Differences with existing wireless network technologies

To understand the specificities and constraints of wireless mesh networks, it is important to position this technology in the landscape of wireless communications. Depending on the network coverage, four distinct groups of wireless network technologies can be identified:

- WPAN (Wireless Personal Area Network): Developed as cable replacement technology. The most widely accepted protocol is IEEE 802.15.1 [15] (standardization of Bluetooth [3]).

[1] We interchangeably use the terms of users, mobile nodes or mobile terminals to refer to this specific network component. Mobile Nodes is a generic term used to refer to users who may not necessarily be mobile (i.e., static wireless terminals).

- WLAN (Wireless Local Area Network): In home and office environments. In infrastructure mode, access to the wired network is achieved through one-hop wireless transmission. In ad hoc mode, users interconnect without the support of any infrastructure. The most commonly accepted Standard is IEEE 802.11 [14].
- WMAN (Wireless Metropolitan Area Network): Intended for larger coverage areas such as cities. Current technological advances render high-throughput wireless connections feasible and offer transmission coverage greater than WLANs'. WMANs standardization effort is undergoing with IEEE 802.16 [16].
- WWAN (Wireless Wide Area Network): For data transmission over large areas such as cities or countries using satellite systems or cellular networks. Although several satellite systems have been successfully launched (Iridium [19], Globalstar [11], etc.), the low offered throughput (around 10 kbps) restricts their practical use to voice applications. On the other hand, high throughput (up to 2 Mbps) cellular networks are able to support a much broader range of applications.

Recently, Wireless Sensor Networks (WSNs) have gained significant importance. WSNs consist of an interconnection of tiny nodes, whose function is to retrieve specific information from the environment and to transmit the result of this sensing operation to a remote destination station. As their coverage depends on the target application (it can potentially be of the size of a WMAN or a WLAN), and given that these networks are data-centric and not user-centric (in that the loss of a node in a sensor network is less important than the information it was sensing), they have been excluded from the above categorization. The architectural differences between these network technologies are summarized in Table 1. The comparisons are performed by considering only the parts of the networks involving wireless communications.

Wireless Mesh Networks can be seen as a combination of WMANs, WLANs and to a certain extent, wireless sensor networks. Data transmission is performed through multi-hop wireless communications and involves the mobile nodes, network gateways and access points. The available bandwidth depends on the underlying network technology, with data rates as high as 54 Mbps. The traffic mix may include multimedia streams and the network is expected to support thousands of mobile users. Wireless mesh networks share similarities with WLANs and WMANs in terms of the fixed infrastructure, and therefore suffer from the same bandwidth limitations and the need to handle user mobility.

2.3 The importance of resource management in wireless mesh networks

In spite of the proliferation of wireless transmission technologies in recent years, wireless bandwidth remains limited compared to wired technologies (LANs, optical, etc.). The impact of environmental conditions and interference on network performance further exacerbates this problem. To meet users' quality-of-service expectations, efficient resource management remains a great challenge in wireless networks.

In general, power control, mobility management, and admission control are resource management problems common to all wireless networks. In addition, cellular networks present the unique challenge of channel allocation whereas routing is a prominent problem in ad hoc networks. As an amalgamation of multiple wireless technologies, WMNs face a combination of these problems, as well as those of network configuration and deployment (see figure 2).

Table 1 Comparison of wireless network architectures

	WWAN		WMAN	WLAN		WPAN	WSN
	Cellular net	Satellite net		Infrastructure	Ad hoc		
Transmission	One-hop	Multihop	One-hop	One-hop	Multihop	Multihop	Multihop
Network Entities	Base stations Mobile nodes	Satellites Mobile nodes	Base stations Mobile nodes	Access points Mobile nodes	Mobile nodes	Mobile nodes	Static nodes Sink
Max. offered Throughput	~2 Mbps	~10 kbps	~1.5 Mbps	~54 Mbps	~54 Mbps	~100 kbps	~100 kbps
Traffic	Multimedia	Voice	Multimedia	Multimedia	Multimedia	Multimedia	Statistics
Users Capacity	Hundreds (per cell)	Hundreds (per satellite)	Hundreds	Dozens (per AP)	Hundreds	Hundreds	Thousands
Trans. Range	~km	~10^5 km	~50 km	~250 m	~250 m	~10 m	~10 m
Frequency Bands	GSM: 800 MHz UMTS: 2 GHz	Iridium: 2 GHz	IEEE 802.16a: 2–11 GHz	2.4/5 GHz	2.4/5 GHz	2.4 GHz	2.4 GHz
Limitations	Fixed deployment cost	Cost Long-term deployment Delay	Fixed deployment	Fixed deployment Bandwidth	Energy Bandwidth	Bandwidth	Energy Processing capabilities Transmission capabilities

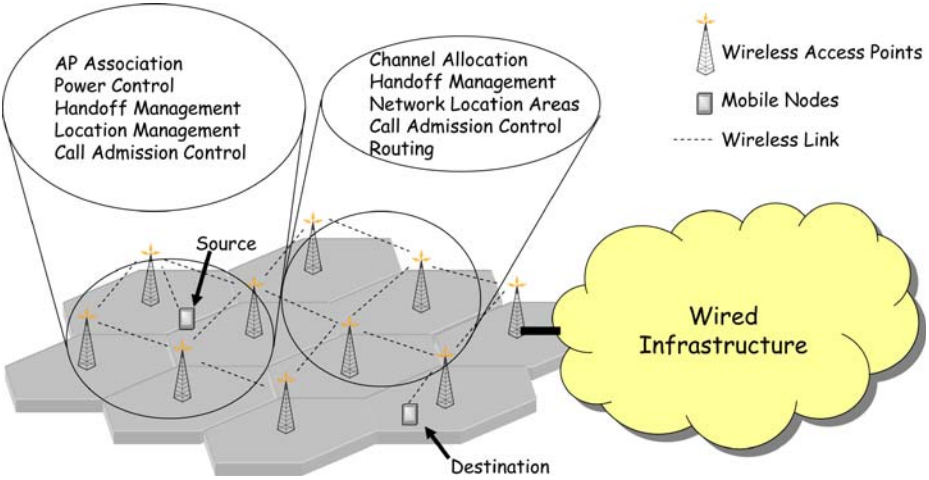

Fig. 2 Resource management challenges: an overview

Resource management in wireless mesh networks encompasses three main areas:

- Network Configuration and Deployment: The specific construct of WMNs (i.e., fixed wireless backbone and mobile end devices) leads to unique requirements in terms of scalability, fault tolerance, path redundancy, QoS assurance, and network coverage. In order to avoid over- or under-dimensioning, resulting in either heavy interference zones or blind spots, it is important to optimize the deployment of the access points (as in traditional cellular networks). For enhanced network performance, it is highly desirable to have channel diversity to prevent wireless interference and support increased number of users. This is traditionally achieved using channel allocation mechanisms. In WMNs, this problem must be extended to multi-hop communication, by considering not only channel allocation between access points and mobile nodes (as per traditional cellular networks), but also between access points.
- Routing: Routing in WMN extends network connectivity to end users through multi-hop relays including the access points and the network gateways. This ultimately should be done while optimizing network resource utilization and accommodating users' QoS requirements. The shared medium characteristics and varying link capacity are some of the crucial design constraints in WMN routing. Unlike ad hoc routing, WMN routing involves primarily a fixed backbone consisting of non-energy constrained nodes (i.e., access points and network gateways), although mobile and energy-constrained wireless nodes (i.e., mobile devices) may also be considered.
- Mobility Management and Admission Control: Seamless user connectivity can be obtained through efficient handoff and location management mechanisms, and appropriate admission control policies. In ad hoc networks, routing and mobility are tightly coupled due to node motion, while in cellular networks, mobility management relies heavily on the underlying infrastructure of base stations, mobile switching centers, and location databases. Wireless mesh networks must reconcile both aspects, while accounting for its multi-hop nature (significantly more communication overhead compared to one-hop communication in cellular networks).

Of the three research areas outlined above, WMN routing may seem to have the most existing, viable solutions, as it has much to benefit from multi-hop routing in ad hoc networks, which has received tremendous research attention and led to many proposed protocols [13]. However, applying these protocols to WMNs may not be optimal. For example, in the MIT Roofnet project [30], a preliminary exploration involved implementing DSDV (Highly Dynamic Destination-Sequenced Distance Vector) [41], an ad hoc routing protocol, in wireless mesh networks. The volume of data traffic severely interfering with the transmission of control packets caused slow path convergence and sub-optimal path setting.

In order to devise better routing protocols for WMNs, we must first analyze the characteristics of WMNs that can impact on the routing. The criteria and performance metrics, against which existing routing protocols from ad hoc, sensor, and WMNs can be evaluated, must also be identified. This can then serve as a basis for deriving the key design features of efficient routing in wireless mesh networks.

3 Wireless mesh networks characteristics

3.1 From a general perspective

Wireless mesh networks are a unique combination of wireless technologies, exhibiting characteristics of each component (ad hoc, cellular and sensor networks). While describing these characteristics, the commonalities and differences between wireless mesh networks and the aforementioned wireless technologies will be emphasized.

- *Transmission medium*. All communications in wireless environments have the following constraints: limited available bandwidth, dynamic changes in link capacity (due to interference, noise, etc.), and asymmetrical links (interference, multipath, etc.). Real world implementations have revealed the limitations of simulations due to the complexity of such environments [33], and have stressed the need for the deployment of testbeds in order to assess the validity of the proposed solutions. The impact of the network conditions becomes more critical in multi-hop wireless networks such as ad hoc and mesh networks, as difficulties in bounding transmission delay and packet loss makes supporting QoS-sensitive applications very challenging.
- *Network deployment*. In cellular networks and infrastructure-based WLANs, base stations (access points) are deployed in specific locations. In Mobile Ad hoc Networks (MANETs), the network topology is dynamically changing as users can be highly mobile although still actively participating in the network operations through packet forwarding mechanisms. Wireless mesh networks, being a hybrid technology, blend a fixed wireless backbone with an edge network consisting of mobile users.
- *Wireless technology*. Whereas base stations in cellular and ad hoc networks are primarily deployed with omni-directional antenna technologies, the fixed backbone of WMNs seems to favor the use of directional antennas for increased throughput. However, the impact of environmental conditions on the network performance needs to be taken into consideration, otherwise the communication can significantly deteriorate due to external phenomena such as wind or rain (causing link failure from disorientation of the antenna).

- *Network infrastructure to support user mobility*. As in ad hoc and cellular networks, users may be mobile. Therefore handoff and location management are important concerns in wireless mesh networks as well. To address these issues, distributed and centralized approaches can be considered. Distributed databases can be deployed in the access points and network gateways to maintain users' profile and manage users' mobility. A centralized approach can also be used, with one entity responsible for maintaining location information. Techniques can be borrowed from cellular technologies and applied to wireless mesh networks, but the communication costs, whereas of little importance in cellular networks (mainly involve fixed part of the network), have adverse effect in bandwidth-constrained wireless mesh networks.

3.2 From a routing perspective

Wireless Mesh Networks exhibit unique characteristics that differentiate them from other wireless and wired technologies. Therefore, existing routing protocols must be revisited in order to consider their adaptability to WMNs. The main differences relating to routing (Table 2) are:

- *Network topology*. A fixed wireless backbone differentiates WMNs from other network types. Therefore, similar to MANETs, communication is performed through multi-hop wireless transmissions. Unlike MANETs, node mobility in the backbone infrastructure is not frequent.
- *Traffic pattern*. In cellular networks and WLANs, data is exchanged between users and access points. In MANETs, traffic can flow between any pair of nodes. In WMNs, data transmission is primarily between the mobile nodes and the network gateway (some similarities can therefore be drawn with sensor networks). Traffic between two nodes in the mesh, although less prominent, should also be considered.
- *Inter-path interference*. WMNs differ from wired networks due to the possibility of interference between disjoint paths. Communication on a wireless link (when considering the use of omni-directional antennas) is open (air medium), whereas wired networks confine their signal to a particular wire. Therefore, a communication between two nodes can have an effect on the transmissions of all neighboring nodes, leading to the well-known problems of hidden and exposed terminals.

Table 2 Routing characteristics summary

	Wired networks	MANETS	WSNs	WMNs
Topology	Static	Mobile	Static	Static
Traffic	Any pair of nodes	Any pair of nodes	Sensor to sink	Mobile node to network gateway (mainly)
Inter-paths interference	No	Yes	Yes	Yes
Link capacity	Fixed	Varying	Varying	Varying
Channel diversity	NA	No	No	Yes

- *Link capacity*. WMNs differ from wired network as the link capacity can vary over time due to the very nature of wireless communications that are sensitive to surrounding interference. This problem is even more critical when multiple technologies use the same frequency band (e.g., ISM band).
- *Channel diversity*. WMNs can benefit from the possibility of introducing channel diversity in the routing process, which is not possible in other wireless networks due to node mobility (MANETs) or energy constraints (WSNs). This technique can significantly reduce inter-nodes interference and increase the overall throughput.

4 Routing

Routing can be referred to as the process of determining the end-to-end path between a source node and a destination node. Although security issues are also a concern in routing mechanisms, solutions for satisfying users' quality of service requirements while optimizing network resource utilization is the primary focus [25]. Although this has been thoroughly studied in conventional networks (wired infrastructure) [5] and mobile ad hoc networks [13] for unicast and multicast communications, the constraints inherent to wireless mesh environments call for new, better-adapted routing protocols.

4.1 Routing protocols: evaluation criteria and performance metrics

1) *Criteria for Categorization*: Routing protocols can be broadly distinguished based on four criteria: routing philosophy, network organization, location awareness and mobility management.

    - Routing philosophy: Routing approaches can be viewed as proactive, reactive, or hybrid. In proactive routing protocols, paths are established regardless of the willingness of a node to transmit data. In reactive (on-demand) routing protocols, routing processes are initiated upon requests. In hybrid routing protocols, some of the nodes may implement a proactive routing protocol and others a reactive routing protocol.
    - Network organization: In a flat organization, all the nodes have the same role in the routing process whereas in a hierarchical organization, some nodes may have specialized functions. For example, in wireless sensor networks, cluster-based routing protocols entail the elections of super nodes (cluster-heads) responsible for data gathering operations.
    - Location awareness: Routing protocols may or may not use localization systems embedded in the network nodes to obtain location information.
    - Mobility management: A WMN must manage the mobility of user nodes throughout the network. As they move, user devices change their point of attachment to the network, connecting to the access point with which they have the strongest signal. Mobility raises several issues, similar to those known in both wired and cellular networks. In MANETs, mobility management has been integrated into the routing process in order to cope with highly mobile nodes. In wired and cellular networks, routing and mobility management have been defined separately although complementary mechanisms.

2) *Performance Metrics*: Depending on the network characteristics, the routing protocols can focus on optimizing one or more performance metrics. The following is a non-exhaustive list including the most commonly used metrics:

- Hop Count: Number of hops between the source and the destination.
- Expected Transmission Count (ETX): This metric is more specific to wireless communications. It accounts for data loss due to medium access contention and environmental hazards, and considers the number of retransmissions needed to successfully transmit a packet over a link [7, 8].
- Expected Transmission Time (ETT): This metric is an enhancement of ETX as it further includes the bandwidth of the link in its computation [9]. This is of particular interest when different network technologies are used (IEEE 802.11a and IEEE 802.11b for instance) in order to favor channel diverse paths.
- Energy consumption: A node energy level can be considered as a routing metric if some nodes are energy-constrained and their involvement in the routing process can lead to path failure if they suffer from energy depletion. This problem is particularly important in MANETs and WSNs.
- Path availability/reliability: This metric estimates the percentage of time a path is available. Node mobility effect can be captured by this metric. It is particularly important in MANETs.

In the remaining of this paper, our discussion will focus on wireless multi-hop networks: mobile ad hoc networks (MANETs), wireless sensor networks (WSNs), and wireless mesh networks (WMNs). The key routing protocols for multi-hop wireless networks are first summarized. Then, they are categorized according to the identified criteria. Finally, the unique characteristics of WMNs are used to discuss why existing routing protocols may not be appropriate for WMNs.

4.2 Brief summary of routing protocols

An exhaustive listing of existing routing protocols for wireless multi-hop networks is beyond the scope of this paper. Instead, as wireless ad hoc networks, wireless sensor networks and wireless mesh networks have similar properties, our discussion is restricted to the key routing protocols proposed for each of these, with particular emphasis on those proposed for wireless mesh networks. These protocols and their classification according to the criteria previously identified are shown in Table 3.

1) *Routing Protocols in MANETs*: In MANETs, many routing protocols have been proposed in the last decade, each attempting to address a few aspects of these networks. [13] provides a comprehensive survey on the subject. Among the proposed protocols, the more note-worthy ones are (chronologically sorted): DSDV (Highly Dynamic Destination-Sequenced Distance Vector) [41], DSR (Dynamic Source Routing) [10], TORA (Temporally Ordered Routing Algorithm) [37], CGSR (Clusterhead-Gateway Switch Routing) [6], GeoCast (Geographic Addressing and Routing) [32], ZRP (Zone Routing Protocol) [53], DREAM (Distance Routing Effect Algorithm for Mobility) [2], LAR (Location-Aided Routing) [23], OLSR (Optimized Link State Routing Protocol) [36], AODV (Ad Hoc On Demand Distance Vector Routing) [1], HSR (Hierarchical State Routing) [38], FSR

Table 3 Routing protocols in wireless environments

	Routing protocols	Proactive	On-demand	Flat	Hierarchical	Location-aware	Metrics	Mobility
Ad hoc	DSDV	X		X		No	Hops	Yes
	DSR		X	X		No	Hops	Yes
	TORA		X	X		No	Hops	Yes
	CGSR	X			X	No	*via* CH	Yes
	GeoCast	X			X	Yes	Hops	Yes
	ZRP	X	X		X	No	Hops (zone)	Yes
	DREAM	X		X		Yes	Hops	Yes
	LAR		X	X		Yes	Hops	Yes
	OLSR	X		X		No	Hops	Yes
	AODV		X	X		No	Hops	Yes
	HSR	X			X	No	*via* CH	Yes
	FSR	X		X		No	Hops	Yes
	TBRPF	X		X		No	Hops	Yes
	LANMAR	X			X	No	Hops (zone)	Group
	GPSR	X		X		Yes	Distance	Yes
WSN	LEACH	X			X	No	Energy	Yes
	PEGASIS		X		X	No	Energy	Yes
	TEEN		X		X	No	Energy	Yes
	SPIN	X		X		No	Energy	No
	Directed Diffusion		X	X		No	Energy	Yes
	TTDD	X			X	Yes	Energy	No
	Random Walk		X	X		No	Energy	No
	Rumor Routing	X	X	X		No	Energy	Limited
WMN	MSR	X	X	X		No	Proprietary	Yes
	SrcRR		X	X		No	ETT	Not considered

(Fisheye State Routing) [39], TBRPF (Topology Broadcast Based on Reverse Path Forwarding) [48], LANMAR (Landmark Ad Hoc Routing Protocol) [40], and GPSR (Greedy Perimeter Stateless Routing) [22].

2) *Routing Protocols in WSNs*: In wireless sensor networks, the choice of a routing protocol depends on the targeted application. The bulk of the research work have focused on two main application domains: environment monitoring and target detection. Environment monitoring applications favor a global network organization. The main contributions are LEACH (Low Energy Adaptive Clustering Hierarchy) [12] and PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [26]. In turn, target detection applications rely on sporadic data retrieval due to the random occurrence of the targeted event. TEEN (Threshold sensitive Energy Efficient Sensor Network protocol) [27], TTDD (Two-Tier Data Dissemination Model) [52], Random Walks [47] and Rumor Routing [4] are widely known contributions in this area. Some other protocols focused more on efficient information dissemination such as SPIN (Sensor Protocols for Informa-

tion via Negotiation) [24] and Directed Diffusion [17]. We refer the reader to [21] for more details on these protocols.

3) *Routing Protocols in WMNs*: Only a few protocols have been developed specifically for WMNs. Several approaches have been considered. MIT (SrcRR [30]) and MeshNetworks (MeshNetworks Scalable Routing [28]) designed new protocols tailored for WMNs. MeshNetworks Scalable Routing (MSR) is a hybrid routing protocol, supposedly able to support highly mobile users and to dynamically adapt to networks conditions. As the protocol is not in the public domain, it is not possible to verify the company's claims. SrcRR is a variation of DSR using the expected transmission time as a metric instead of the number of hops. In other words, the shortest paths are determined based on least packet loss.

   Other works have focused on enhancing existing routing protocols with new routing metrics more appropriate for WMNs. Indeed, the fixed wireless backbone allows a better estimation of the link quality through regular measurements. It is also possible to introduce channel diversity in the network infrastructure so as to reduce interference and increase overall throughput [9, 43].

4) *Comparisons and Observations*: From Table 3, it can be seen that in MANETs, the most favored research approach is proactive routing; in sensor networks both proactive and reactive approaches are equally used; and in mesh networks, routing approaches are mainly reactive or hybrid. The choice of a routing technique is made based on the network characteristics with the greatest impact on routing. These are:

   - Network size: The choice of a routing protocol is highly dependent on the network size and node density. For instance, if the network is large, flooding should be avoided, whereas this solution is satisfactory when the number of nodes is small.
   - Node mobility: It is important to evaluate the users degree of mobility in order to design protocols adapted to the frequency of handoffs and route updates.
   - Traffic patterns: Traffic characteristics and traffic type can have a major impact on routing design and resource management. For instance, when the network is exposed to heavy traffic volumes, it is necessary to include load balancing techniques in the routing, in order to optimize network resource utilization and avoid congestion.

Control overhead is another important design criterion. The number of control packets generated by the routing mechanism impacts the data transmission and offered throughput, which needs to be evaluated.

Although reactive routing protocols are able to address node mobility, the significant overhead and delay pertinent to reactive protocols are not acceptable for delay-sensitive applications in energy-constrained networks. In wireless sensor networks, routing protocols have been developed in accordance with the supported applications. If data is only sent sporadically (e.g., target detection applications), proactive routing protocols may not be the best choice. On the other hand, environmental monitoring applications require constant data retrieval and hence justify the use of proactive routing protocols. In wireless mesh networks, the routing strategy should also be selected based on these factors. First, environmental conditions have a significant impact on data transmission. Implementing a proactive routing protocol based on metrics such as ETT or ETX is difficult as the link capacity fluctuates overtime and the convergence time can be significant when the control packets have to compete with data traffic. However, other parameters can be very helpful for making the routing decisions. For instance, access point location is readily available and tends to remain static over long periods of time.

Implementing a flat or hierarchical routing protocol depends on the network complexity and the nodes capabilities. For instance, hierarchical routing protocols have been proposed in scenarios where some nodes embed localization systems and can therefore serve as reference points. This approach is also popular in energy-constrained wireless sensor networks. The same mechanism may also be leveraged in mesh networks for mobility management.

The choice of performance metrics to be used is also influenced by the network specifics. It has been shown [9] that the number of hops constitute the best routing metric when mobility is involved. However, in wireless mesh networks, the presence of a fixed backbone can significantly impact the routing design. By gathering relevant information on the actual physical environment, such as interference level, more informed resource management can be performed.

4.3 How to design a WMN routing protocol?

To capture the essence of what has been discussed so far, the following questions must be posed to help guide the design of an efficient routing protocol suitable for wireless mesh networks.

- *Which performance metric(s) should be used?* The nature of a WMN demands that the chosen routes be efficient. However, it is not entirely clear what should be optimized. As long as the degree of node mobility is not high, [9] has shown the advantage of using the expected transmission time to account for link capacity and loss rate in the routing decision. Conversely, when the degree of node mobility is high, minimizing the hop count is still the most sensible decision.
- *What hardware technologies will be used?* Technologies such as directional antennae have been considered in ad hoc networks. However due to user mobility they required complicated solutions. This option can be considered in wireless mesh networks, depending on deployment scenarios and the feasibility of line-of-sight communications. However, this will considerably change the network's properties, as link properties and network connectivity will be impacted. This may demand a drastic re-thinking of routing approaches, as links and interactions between links must be re-considered.
- *Proactive or reactive routing protocol? Or hybrid?* Even though the presence of a fixed wireless backbone seems to favor a proactive routing protocol, real-world experiments conducted as part of the MIT Roofnet project [30] have revealed the impact of changing network conditions on the routing protocols. In some cases, the number of updates could not be disseminated fast enough due to the contention of control traffic with data traffic, leading to non-optimal routing decisions. A hybrid routing protocol seems a more sound approach given that the wireless backbone will not suffer from node outages at a nearly or the same frequency as in MANETs or sensor networks.

- *Link or path optimization?* Considering the impact of the network environment on the routing decision, it is not clear if it is preferable to find an optimal path or use a local optimization strategy based on optimal links.
- *Integrated Routing and Mobility Management?* Current IP mobility is separate from the underlying IP routing protocol, but uses it in order to tunnel packets to their destination. However, micromobility protocols such as Cellular IP [49] and Hawaii [42] have implemented custom routing functionality. Ad hoc protocols take this even further by integrating all mobility mechanisms within the context of the routing protocol. Handling this (ad hoc) level of mobility is not needed when devising a routing protocol for WMNs. However, as user mobility is an integral part of the network, the routing and mobility management must either be integrated, or must interact effectively with each other.

5 Conclusion and future research

With the rise of user expectation of anywhere connectivity and quality of service guarantees, new wireless technologies are sought after for their versatility, ease of deployment, and low cost. Wireless mesh networks present a promising solution by extending network coverage based on mixture of wireless technologies through multi-hop communications. WMNs exhibit several prominent characteristics that make them stand apart from traditional wired or wireless networks, and hence call for new resource management techniques.

Routing in multi-hop wireless networks has always been a challenging research avenue. Previous works in this area have focused on ad hoc networks. However, the disparity between mesh and ad hoc networks is significant enough to question the suitability of ad hoc routing protocols for mesh networks.

In this paper, the characteristics of wireless mesh networks have been discussed and compared with the properties of other wireless networks. Existing routing protocols have been categorized according to these properties. We argue that new routing protocols specifically adapted for WMNs are needed. A set of design questions have been raised, relating to WMN routing. These questions require further investigations, and consideration in the development of protocols for WMNs.

We hope that this paper will help in shaping future research in this area by providing a more concise view and problem definition, design requirements and constraints, and suggestions for possible research directions.

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References

1. Ad hoc On-Demand Distance Vector (AODV) Routing (2003, February) http://www.ietf.org/internet-drafts/draft-ietf-manet-aodv-13.txt. Internet Draft
2. Basagni S, Chlamtac I, Syrotiuk VR, Woodward BA (1998) A distance routing effect algorithm for mobility (dream). In: Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking, pp 76–84

3. Bluetooth. http://www.bluetooth.com
4. Braginsky D, Estrin D (2002) Rumor routing algorithm for sensor networks. In: Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications, pp 22–31
5. Chen S, Nahrstedt K (1998, November/December) An overview of quality of service routing for next-generation high-speed networks: problems and solutions. IEEE Netw 12(6):64–79
6. Chiang C-C, Gerla M (1997, October) IEEE 6th international conference on universal personal communications record. In: Routing and Multicast in Multihop, Mobile Wireless Networks, vol 2, pp 546–551
7. De Couto DSJ, Aguayo D, Bicket J, Morris R (2003) A high-throughput path metric for multi-hop wireless routing. In: Proceedings of the 9th Annual International Conference on Mobile Computing and Networking, pp 134–146
8. Draves R, Padhye J, Zill B (2004, August) Comparison of routing metrics for static multi-hop wireless networks. In: Proceedings of the 2004 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications
9. Draves R, Padhye J, Zill B. (2004) Routing in multi-radio, multi-hop wireless mesh networks. In: Proceedings of the 10th Annual International Conference on Mobile Computing and Networking, pp 114–128
10. The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks (DSR) (2003, April) http://www.ietf.org/internet-drafts/draft-ietf-manet-dsr-09.txt. Internet Draft
11. Globalstar. http://www.globalstar.com
12. Heinzelman WR, Chandrakasan A, Balakrishnan H (2000, January) Energy-efficient communication protocol for wireless microsensor networks. In: Proceedings of the 33rd Annual Hawaii International Conference on System Sciences, vol 2
13. Hong X, Xu K, Gerla M (2002, July–August) Scalable routing protocols for mobile ad hoc networks. IEEE Netw 16(4)
14. IEEE 802.11. http://grouper.ieee.org/groups/802/11/
15. IEEE 802.15.1. http://www.ieee802.org/15/pub/tg1.html
16. IEEE 802.16. http://www.ieee802.org/16/
17. Intanagonwiwat C, Govindan R, Estrin D, Heidemann J, Silva F (2003) Directed diffusion for wireless sensor networking. IEEE/ACM Trans Netw 11(1):2–16
18. Intel. http://www.intel.com
19. Iridium. http://www.iridium.com
20. Jangeun J, Sichitiu ML (2003, October) The nominal capacity of wireless mesh networks. IEEE Wireless Communications 10(5):8–14
21. Jiang Q, Manivannan D (2004, January) Routing protocols for sensor networks. In: Proceedings of the 1st Consumer Communications and Networking Conference
22. Karp B, Kung HT (2000) Gpsr: greedy perimeter stateless routing for wireless networks. In: Proceedings of the 6th Annual International Conference on Mobile Computing and Networking, pp 243–254
23. Ko Y-B, Vaidya NH (1998) Location-aided routing (lar) in mobile ad hoc networks. In: Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking, pp 66–75
24. Kulik J, Heinzelman W, Balakrishnan H (2002) Negotiation-based protocols for disseminating information in wireless sensor networks. Wirel Netw 8(2/3):169–185
25. Kurose J, Ross K (2002) Computer networking: a top-down approach featuring the internet. Addison-Wesley, Reading, Massachusetts
26. Lindsey S, Raghavendra C, Sivalingam KM (2002) Data gathering algorithms in sensor networks using energy metrics. IEEE Trans Parallel Distrib Syst 13(9):924–935
27. Manjeshwar A, Agrawal DP (2001, April) Teen: a routing protocol for enhanced efficiency in wireless sensor networks. In: Proceedings of 15th International Parallel and Distributed Processing Symposium, pp 2009–2015
28. Meshnetworks. http://www.meshnetworks.com
29. Microsoft. http://www.research.microsoft.com/
30. MIT Roofnet. http://www.pdos.lcs.mit.edu/roofnet/
31. Motorola Canopy. http://motorola.canopywireless.com/
32. Navas JC, Imielinski T (1997) Geocastgeographic addressing and routing. In: Proceedings of the 3rd Annual ACM/IEEE International Conference on Mobile Computing and Networking, pp 66–76
33. Newport C, Kotz D, Elliott C (2003, July) The mistake axioms of wireless-network research. Technical report TR2003-467, Dartmouth CS Department

34. Nokia. http://www.iec.org/events/2002/natlwireless_nov/featured/tf2_beyer.pdf
35. Nortel Networks Wireless Mesh Networks Solution. http://www.nortelnetworks.com/solutions/wrlsmesh/architecture.html
36. Optimized Link State Routing Protocol (OLSR) (2003, October) Rfc3636.
37. Park VD, Corson MS (1997, April) A highly adaptive distributed routing algorithm for mobile wireless networks. In: Sixteenth Annual Joint Conference of the IEEE Computer and Communications Societies, vol 3, pp 1405–1413
38. Pei G, Gerla M, Hong X, Chiang C-C (1999, September) A wireless hierarchical routing protocol with group mobility. In: IEEE Wireless Communications and Networking Conference, vol 3, pp 1538–1542
39. Pei G, Gerla M, Chen T-W (2000, June) Fisheye state routing: a routing scheme for ad hoc wireless networks. In: IEEE International Conference on Communications, vol 1, pp 70–74
40. Pei G, Gerla M, Hong X (2000) Lanmar: landmark routing for large scale wireless ad hoc networks with group mobility. In: Proceedings of the 1st ACM International Symposium on Mobile ad Hoc Networking & Computing, IEEE, pp 11–18
41. Perkins CE, Bhagwat P (1994) Highly dynamic destination-sequenced distance-vector routing (dsdv) for mobile computers. In: Proceedings of the Conference on Communications Architectures, Protocols and Applications, pp 234–244
42. Ramjee R, Varadhan K, Salgarelli L, Thuel SR, Wang S-Y, La Porta T (2002) Hawaii: a domain-based approach for supporting mobility in wide-area wireless networks. IEEE/ACM Trans Netw 10(3):396–410
43. Raniwala A, Gopalan K, Chiueh T (2004) Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks. In SIGMOBILE Mob Comput Commun Rev 8(2), ACM Press
44. Rayner K (2003, October–November) Mesh wireless networking. Communications Engineer 1(5):44–47
45. Schrick B, Riezenman MJ (2002, June) Wireless broadband in a box. IEEE Spectrum 39(6):38–43
46. Scott Corson M, Macker J, Batsell SG (1996, October) Architectural considerations for mobile mesh networking. In: Proceedings of Military Communications Conference (MILCOM '96), vol 1, pp 224–229
47. Servetto SD, Barrenechea G (2002) Constrained random walks on random graphs: routing algorithms for large scale wireless sensor networks. In: Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications, pp 12–21
48. Topology Broadcast based on Reverse Path Forwarding (2004, February) draft-ietf-manet-tbrpf-11.txt.
49. Valkó AG (1999) Cellular IP: a new approach to internet host mobility. SIGCOMM Comput Commun Rev 29(1):50–65
50. Whitehead P (2000, September) Mesh networks; a new architecture for broadband wireless access systems. In: IEEE Conference on Radio and Wireless (RAWCON), pp 43–46
51. Xue Q, Ganz A (2002, July) Qos routing in mesh-based wireless networks. Int J Wirel Inf Netw 9(3):179–190
52. Ye F, Luo H, Cheng J, Lu S, Zhang L (2002) A two-tier data dissemination model for large-scale wireless sensor networks. In: Proceedings of the 8th Annual International Conference on Mobile Computing and Networking, pp 148–159
53. The Zone Routing Protocol (ZRP) for Ad Hoc Networks (1999, June) draft-ietf-manet-zone-zrp-02.txt.

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