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) prevent their straight forth application to WMNs.

To have a clear and precise focus on future research in WMN routing, we first describe the characteristics of WMNs that have a high impact on routing. Then we define a set of criteria against which the existing routing protocols from ad hoc, sensor, and WMNs can be evaluated and performance metrics identified. This can serve as the basis for deriving the key design features for routing in wireless mesh networks. This paper could help to guide and refocus future works in this area.

I. Introduction

Extending high-speed IP connectivity to the "last mile" is an open and on-going research problem with no satisfactory solution. Full end-to-end optical networks are a potential solution. However, the initial

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investment costs of such wide spread deployment, and the difficulty of deployment in some environment settings (established urban areas, wilderness, etc.), have prevented its realization in access networks. Wireless Mesh Networks (WMNs), consisting of wireless access and wireless backbone networks, present an attractive alternative. In contrast to optical networks, WMNs have low investment overhead and are fast to deploy. 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 [36], Microsoft [34], Motorola [8] and Intel [23], are actively promoting wireless mesh networks as a full IP solution. Initial field tests [45] [47] [51] have demonstrated WMN's tremendous potentials and market value. WMNs cover a diverse set of existing and emerging wireless technologies, including cellular technologies, ad hoc networks, and sensor networks. 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 demand for QoS guarantees.

This paper provides an overview of resource management issues in WMNs and particularly focuses on the routing problem. We evaluate the need for developing new routing mechanisms tailored for wireless mesh networks taking into account the unique characteristics of WMNs.

The remainder of the paper is organized as follows. Section II provides a general overview of wireless mesh networks and the associated resource management issues. Section III identifies the characteristics of wireless mesh networks. Routing issues are discussed in Section IV. We conclude this paper in Section V.

II. Wireless Mesh Networks

A. 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. 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 distinctions can be generally made regarding the following perspectives:

- Network components: The inclusion of mobile nodes as part of the wireless mesh network architecture differentiates current proposals. MIT Roofnet [46] and Nortel Networks' solutions [49] 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 [33] considers meshing between access points, as well as between mobile nodes.

- Degrees of mobility: Some early work in WMNs [11] drew equivalence 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 [15] 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 gives ground to question the suitability of applying existing protocols initially developed for ad hoc networks in the context of 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 [25]. Traffic can also flow between any pair of nodes (as in ad hoc networks).

To form a common understanding on what a wireless mesh network is, we suggest the following definition that is general enough to encompass most current network architectures, with regard to the specifics of a mesh network:

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.

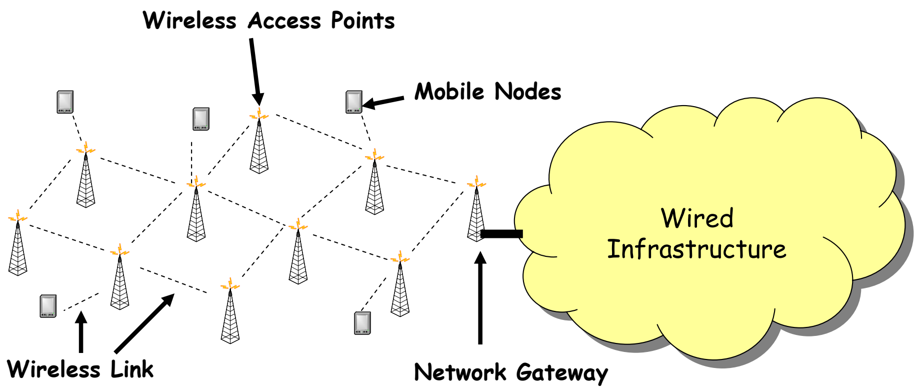

Fig. 1. Example of Wireless Mesh Network Topology

2) Our view of the wireless mesh network architecture: Contrary to [52], which regards a mesh network as composed of only two different entities, the mobile nodes and the access points, we adopt a more general view of a mesh network (similar to [49]). We consider the mesh network architecture as 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.
- 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.). They can be connected to wireless or wired users. The APs are assumed static, with a low failure probability and are not power constrained. 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 the mesh 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).

[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).

B. 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 [2] (standardization of Bluetooth [6]).
- WLAN (Wireless Local Area Network): in home and office environments. In infrastructure mode, access to the wired network is achieved through 1-hop wireless transmission. In ad hoc mode, users interconnect without the support of any infrastructure. The most commonly accepted Standard is IEEE 802.11 [1].
- 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 [3].
- 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 [24], Globalstar [18], etc.), the low offered throughput (around 10kbps) restricts their practical use to voice applications. On the other hand, high throughput (up to 2Mbps) cellular networks are able to support a much broader range of applications.

Recently, Wireless Sensor Networks (WSNs) 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, we excluded them from the above categorization. The architectural differences between these network technologies are summarized in Table I. Our comparisons are performed by considering only the parts of the networks involving wireless communications.

TABLE I
COMPARISON OF WIRELESS NETWORK ARCHITECTURES

	WWAN		**WMAN**	**WLAN**		**WPAN**	**WSN**
	Cellular Net	**Satellite Net**		**Infrastructure**	**Ad Hoc**		
Transmission	1-hop	multihop	1-hop	1-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	∼2Mbps	∼10kbps	∼1.5Mbps	∼54Mbps	∼54Mbps	∼100kbps	∼100kbps
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	$\sim10^5$km	∼50km	∼250m	∼250m	∼10m	∼10m
Frequency Bands	GSM: 800MHz UMTS: 2GHz	Iridium: 2GHz	IEEE 802.16a: 2-11GHz	2.4/5GHz	2.4/5GHz	2.4GHz	2.4GHz
Limitations	- Fixed Deployment Cost	- Cost - Long-term Deployment - Delay	Fixed Deployment	- Fixed Deployment - Bandwidth	- Energy - Bandwidth	- Bandwidth	- Energy - Processing Capabilities - Transmission Capabilities

Wireless Mesh Networks can be seen as a combination of WMANs, WLANs and to 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 54Mbps. The traffic mix may include multimedia streams and the network is expected to support thousands of mobile users. Wireless mesh networks share similarities with WLAN and WMAN in terms of the fixed infrastructure, and therefore suffer from the same bandwidth limitations and must handle user mobility.

C. 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 its wire line counterpart. 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).

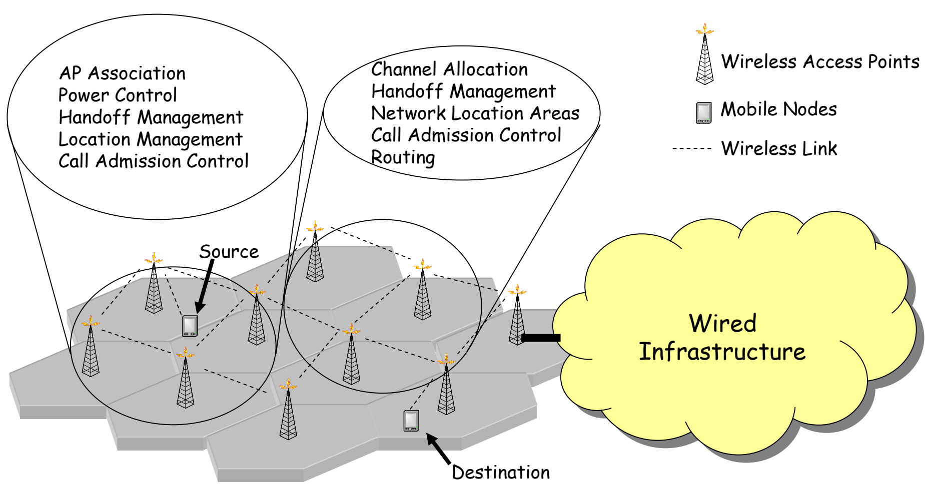

Fig. 2. Resource management challenges: an overview

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 under-dimensioning and over-dimensioning resulting in heavy interference zones or resulting in 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 both mobile and energy-constrained wireless nodes (i.e. mobile devices) and a fixed backbone consisting of non-energy constrained nodes (i.e. access points and network gateways).
- 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 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 [21]. However, applying these protocols to WMNs may not be optimal. For example, in the MIT Roofnet project [46], a preliminary exploration involved implementing DSDV (Highly Dynamic Destination-Sequenced Distance Vector) [42], 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. We should also identify the criteria and performance metrics against which existing routing protocols from ad hoc, sensor, and WMNs can be evaluated. This can then serve as a basis for deriving the key design features of efficient routing in wireless mesh networks.

III. Wireless Mesh Networks Characteristics

A. From a general perspective

Wireless mesh networks are a unique combination of wireless technologies, exhibiting characteristics from ad hoc, cellular and sensor networks. While describing these characteristics, we intend to emphasize the commonalities and differences between wireless mesh networks and the aforementioned wireless technologies.

- *Transmission medium*. All communications in wireless environments have the following similar constraints: limited available bandwidth, dynamic change of 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 [13], 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 multihop 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 omnidirectional 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.

B. From a routing perspective

Wireless Mesh Networks exhibit unique characteristics that differentiate them from other wireless and wired technologies and put forth the necessity to revisit actual routing protocols and question their adaptability to WMNs. The main differences concern:

- *Network topology*. A fixed wireless backbone differentiate WMNs from other network infrastructure. Therefore and similarly to MANETs, communication is performed through multihop wireless transmissions, but 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), but traffic between two nodes in a 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 point-to-multipoint as opposed to point-to-point communications in wired networks. Therefore, a communication between two nodes can impact the transmission of neighboring nodes, leading to the well-known problems of hidden and exposed terminals.
- *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.

TABLE II
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

IV. 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 a concern in routing mechanisms, we mainly focus on solutions satisfying users' quality of service requirements while optimizing network resource utilization [30]. Although this has been thoroughly studied in conventional networks (wired infrastructure) [9] and mobile ad hoc networks [21] for unicast and multicast communications, the constraints inherent to wireless mesh environments call for new more adapted routing protocols.

A. 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 (clusterheads) 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 [12] [14].
- Expected Transmission Time (ETT): this metric is an enhancement of ETX as it further includes the bandwidth of the link in its computation [15]. 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, we will focus our discussion on wireless multihop networks: mobile ad hoc networks (MANETs), wireless sensor networks (WSNs), and wireless mesh networks (WMNs). We first summarize the key routing protocols for multihop wireless networks and categorize them according to the identified criteria. We highlight the unique characteristics of WMNs and discuss why existing routing protocols may not be appropriate for WMNs.

B. Brief Summary of Routing Protocols

An exhaustive listing of existing routing protocols for wireless multihop networks is beyond the scope of this paper. Instead, as wireless ad hoc networks, wireless sensor networks and wireless mesh networks have similar properties, we restrict our discussion 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 III.

1) Routing Protocols in MANETs: In MANETs, many routing protocols have been proposed in the last decade, each attempts to address a few aspects of these networks. We refer the reader to [21] for 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) [42], DSR (Dynamic Source Routing) [17], TORA (Temporally-Ordered Routing Algorithm) [38], CGSR (Clusterhead-Gateway Switch Routing) [10], GeoCast (Geographic Addressing and Routing) [35], ZRP (Zone Routing Protocol) [16], DREAM (Distance Routing Effect Algorithm for Mobility) [4], LAR (Location-Aided Routing) [28], OLSR (Optimized Link State Routing Protocol) [37], AODV (Ad Hoc On Demand Distance Vector Routing) [20], HSR (Hierarchical State Routing) [39], FSR (Fisheye State Routing) [40], TBRPF (Topology Broadcast Based on Reverse Path Forwarding) [5], LANMAR (Landmark Ad Hoc Routing Protocol) [41], and GPSR (Greedy Perimeter Stateless Routing) [27].

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) [19] and PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [31]. In turn, target detection applications rely on sporadic data retrieval due to the random occurence of the targeted event. TEEN

(Threshold sensitive Energy Efficient Sensor Network protocol) [32], TTDD (Two-Tier Data Dissemination Model) [53], Random Walks [48] and Rumor Routing [7] are widely known contributions in this area. Some other protocols focused more on efficient information dissemination such as SPIN (Sensor Protocols for Information via Negotiation) [29] and Directed Diffusion [22]. We refer the reader to [26] for more details on these protocols.

3) Routing Protocols in WMNs: Only few protocols have been developed for WMNs. Several approaches have been considered. MIT (SrcRR [46]) and MeshNetworks (MeshNetworks Scalable Routing [33]) designed new protocols specifically 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 [44] [15].

4) Comparisons and Observations: From Table III, we observe 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 hightly 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 embedd 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 [15] 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.

TABLE III
ROUTING PROTOCOLS IN WIRELESS ENVIRONMENTS

	Routing Protocols	**Proactive**	**On-Demand**	**Flat**	**Location-aware**	**Metric**	**Integrated Mobility**
Ad Hoc	DSDV	X		X	No	Hops	Yes
	DSR		X	X	No	Hops	Yes
	TORA		X	X	No	Hops	Yes
	CGSR	X			No	via CH	Yes
	GeoCast	X			Yes	Hops	Yes
	ZRP	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			No	via CH	Yes
	FSR	X		X	No	Hops	Yes
	TBRPF	X		X	No	Hops	Yes
	LANMAR	X			No	Hops (zone)	Group
	GPSR	X		X	Yes	Distance	Yes
WSN	LEACH	X			No	Energy	Yes
	PEGASIS		X		No	Energy	Yes
	TEEN		X		No	Energy	Yes
	SPIN	X		X	No	Energy	No
	Directed Diffusion		X	X	No	Energy	Yes
	TTDD	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	-
	PWRP	X	X	X	No	Proprietary	-
	MMRP	X		X	No	TBD	-

C. How to Design a WMN Routing Protocol?

To capture the essence of what we have 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)?* As long as the degree of node mobility is not high, [15] has shown the advantage of using the expected transmission time to account for link capacity and loss rate in the routing decision. Inversely, when the degree of node mobility is high, minimizing the hop count is still the most sensible decision.
- *Which hardware technology?* Whereas the use of directional antenna is considered prohibitive in ad hoc networks due to user mobility, this option can be considered in wireless mesh networks, depending on the deployment scenario and the feasibility of line-of-sight communications.
- *Reactive, proactive or hybrid routing protocol?* 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 [46] 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 network environment on the routing decision, it may or may not be preferable to find an optimal path or use local optimization strategy based on optimal links.
- *Integrated Routing and Mobility Management?* Current IP mobility is separate from but use the underlying IP routing protocol in order to tunnel packets to their destination. However, micromobility protocols such as Cellular IP [50] and Hawaii [43] have implemented custom routing functionality. Ad hoc protocols take this even further by integrating all mobility mechanisms within the context of the routing protocol. Such level of mobility is do not need to be considered 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.

V. 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, we have discussed the characteristics of wireless mesh networks, compared them with other wireless networks and categorized existing routing protocols. We found that new routing protocols specifically adapted for WMNs are needed. We have also raised a set of design questions related to WMN routing and that require further investigations.

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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