A Survey on Routing Protocols that really Exploit Wireless Mesh Network Features

José Núñez-Martínez, Josep Mangues-Bafalluy
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Parc Mediterrani de la Tecnologia – Av. Carl Friedrich Gauss, 7 – 08860 Castelldefels – Barcelona – Spain
Tel: +34 936452900, Fax: +34 936452901
Email: {jose.nunez, josep.mangues}@cttc.cat

Abstract— **The design of a routing protocol that really exploits the specific features of a Wireless Mesh Network (WMN) still remains a challenge. The expected additional benefit, with respect to those that do not or cannot exploit them, is an increase in overall throughput supported by the network. The static and non-power constrained nature of backbone nodes allow offering some exploitable features towards this goal, such as multi-radio and multi-channel support, stability, and increased CPU and storage capabilities. Such features have a strong impact on the design of the routing scheme, which makes inefficient to port existing solutions from wired and other wireless networks. As a consequence, in recent years, many alternative routing protocols have been proposed for WMNs. This survey paper presents the current state-of-the-art of routing protocols specifically designed for WMNs that try to maximize the throughput transferred by the network. First, a classification of routing protocols is provided. Second, the routing architecture is decomposed into three major building blocks. Open research issues related to each building block are also discussed. And finally, the main characteristics of the building blocks for each relevant routing protocol in the taxonomy are summarized.**

Index Terms—**routing, wireless mesh network, multi-radio, multi-channel, multi-rate, opportunistic routing, overview, network coding**

I. INTRODUCTION

WMNs [25] have various application scenarios, such as building automation, wireless community networks, or providing an easy and economical last-mile Internet access. Instead of deploying costly wired infrastructure, WMNs offer a low-cost multi-hop wireless backbone. This has generated considerable interest from industry, e.g. [27] or [28].

However, there are still several issues to be resolved. One of the major problems to be tackled is the design of an optimal routing protocol. In fact, although many routing protocols from wired and other wireless networks can be deployed in WMNs, they do not fully exploit their singular characteristics.

On the one hand, wired-based routing protocols assume each link in the network can only be in two states in terms of connectivity: either the wireless link works perfectly or it does not work at all. Additionally, they usually rely on the hop-count metric, which is not suitable for WMNs. Shortest paths in terms of number of hops often lead to the selection of paths composed of bad quality links. The reason for this is that selected links are the longest ones in terms of distance, hence decreasing the received signal-to-noise ratio (SNR) at the nodes and generating more interference to neighboring nodes using the same channel. Moreover, in protocols for wired networks, the typical volume of routing overhead is not a concern, since they rely on links in the order of Gigabits per second.

However, wireless links cannot be compared with wired links in terms of bandwidth, even under ideal wireless channel conditions i.e., perfect line of sight and no interference. Furthermore, wireless links are subject to high variability. But despite all this, WMNs are expected to allow running high throughput Internet applications. Therefore, the design of high throughput routing protocols able to appropriately deal with wireless links becomes a necessity.

In wireless ad-hoc networks, the main design goal of routing protocols is end-to-end connectivity maintenance. Moreover, transmitting a packet is highly costly due to node energy constraints. Therefore, at the routing level, the research is mainly focused on designing low control overhead routing techniques to deal with frequent route breaks due to mobility or node failures.

By contrast, with emerging WMNs, the efforts towards the design of routing protocols have been shifted from merely maintaining connectivity to obtaining high throughput end-to-end paths [40]. The WMN backbone is composed of static and non-power constrained Wireless Mesh Routers (WMRs). As a consequence, mobility and energy limitations are not a concern anymore for WMRs [24]. Then, besides maintaining, amongst others, reliability and scalability as desirable properties, the main new target for a routing protocol for WMNs is throughput maximization, even at the expense of generating more routing overhead, which deserves a secondary role [40].

This paper provides a comprehensive survey of practical WMN routing protocols for throughput maximization by considering the unique properties of WMNs. As stated in [40], the main performance metric for evaluating a routing protocol for WMNs is

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throughput. Therefore, the main goal of a routing protocol for WMNs should be to maximize the throughput received by the destination of a single flow or the overall throughput of the WMN. In this paper, we focus on routing protocols for WMNs that have throughput as their primary metric/target for measuring their performance.

In addition, the routing protocols presented in this paper are implementable in the sense that we restrict it to those protocols that have been fully implemented in a real testbed or in a network simulator.

We provide a classification of routing protocols based on the characteristics exploited that are unique to WMNs. Additionally, we also identify the three building blocks a unicast routing protocol for WMNs may be decomposed into. Open research issues that future routing protocols may consider when designing each building block are also discussed.

The classification proposed is orthogonal to state-of-the-art classification approaches. Existing recent surveys in the literature are not specifically focused on WMN characteristics ([30], [36],) or at least, the WMNs characteristics taken into account in this work. By contrast, in this paper, the criteria for grouping routing protocols are unique to WMNs. Moreover, this paper presents what is, up to our knowledge, the first study of research work specifically developed for WMNs for each of the building blocks a routing protocol is composed of.

The rest of this paper is organized as follows. Section II outlines the main limitations and advantages of WMNs. Section III summarizes the key decisions in the design of a routing protocol. Section IV presents a novel way to classify routing protocols based on the WMN properties exploited to maximize throughput. Section V decomposes the routing architecture into building blocks and identifies their open research issues. Section VI explains the relevant design choices made by each routing protocol for each building block. Finally, section VII concludes the paper.

II. WMNS: FRAMEWORK, CONSTRAINTS & ADVANTAGES

A WMN (Figure 1) is a self-organized packet-switched network composed of nodes with wireless communication capabilities and organized in a mesh topology. The nodes composing WMNs may be categorized as Wireless Mesh Routers (WMRs) and Wireless Mesh Clients (WMCs). WMRs are static and non-power constrained and WMCs are potentially mobile. WMRs may, in turn, be divided into two types: 1) WMRs directly connected to the Internet (usually referred to as gateways), and 2) WMRs used to reach the gateways or other WMRs by traversing the multi-hop mesh topology. Throughout this paper, we refer to the former as gateways and to the latter as WMRs. Due to space constraints, we will merely focus on the routing issues between static nodes in WMNs (backbone WMNs). Mobility management deserves a full survey paper on its own. For the same reasons, this paper does not deal with the integration of routing between the wired Internet and WMNs.

Furthermore, we are assuming all the WMRs in the WMN are peers (i.e., they have the same functionalities and processing capabilities in terms of routing). This is different from relay-based wireless networks which involve the addition of lightweight nodes (i.e., relays) with fewer processing capabilities and functionalities than WMRs. A proposal in this direction can be found in [42].

The WMN routing problem may be defined as follows: given a source WMR (or gateway) and a destination WMR (or gateway), provide the necessary routing paths satisfying a number of constraints related to WMNs. A routing path is a set of WMRs and wireless links connecting source and destination. The more relevant constraints a WMN must handle are outlined in subsection II.A. On the other hand, a WMN does not only introduce limitations for the design of a high-throughput routing protocol. The most important advantages are identified in subsection II.B.

A. *Constraints*

The constraints of a WMN may be seen as a mixture of constraints inherited from wired and/or other wireless networks. In fact, WMNs share properties present in both wired and wireless networks. In particular, we highlight some of the most relevant limitations commonly driving the design of a routing protocol for WMNs. These relevant constrains are grouped based on whether they are specifically present in a wireless network environment or not (i.e., the constraint is present in any generic network environment).

1) *Common to all Networks*

Heterogeneous traffic demand. Applications running over a WMN are similar to those found on the Internet. Thus, traffic demands can differ from a reliable file transfer to real-time services, such as voice or video. A routing protocol must appropriately handle traffic patterns generated by different applications. Moreover, different applications and users may have different QoS requirements.

Undefined number of nodes (WMRs) and interfaces. The number of WMRs in a WMN may strongly vary. Additionally, the number of wireless radio interfaces per WMR may also vary. These, a priory unknown, characteristics pose additional challenges to the design of a generic routing protocol for WMNs. Thus, the routing protocol must support different network sizes and number of interfaces per WMR. This is unlike in ad-hoc networks, for which sizes may be smaller and nodes in general have a single interface, in general.

2) *Wireless Networks*

Wireless medium instability. Theoretical maximum rates are only achievable under ideal conditions. Though WMRs are static, in real-world deployments, the capacity of wireless links is conditioned by interference, distance, and fading. This leads to highly variable links, which may even cause total path degradation.

Scarce wireless bandwidth. A WMN is expected to provide similar bandwidth to that of the wired Internet. Several efforts at the physical layer, such as Orthogonal Frequency Division Multiplexing (OFDM) and Multiple

Input Multiple Output (MIMO) systems have been developed to provide higher rates. But despite these recent advances at the physical layer, WMNs still have bandwidth limitations compared to the wired infrastructure.

B. Advantages

A WMN can also offer several advantages. The advantages are a combination of some desirable properties from wired and wireless networks. Their combination is, in general, not present in any other known network environment. The more important advantages are summarized as follows:

Stable backbone. Unlike in other wireless networks, WMRs from WMNs are usually static and non-power constrained. Therefore, a WMR can be augmented with additional hardware equipment, like storage units and multiple radios. Moreover, WMR computations are not energy constrained. Therefore, a stable backbone may facilitate the design of a routing protocol.

Wireless broadcast medium. In a wireless environment, the broadcast medium offers the possibility to transmit a packet to several potential next-hops in transmission range at the same cost of a unicast transmission. This provides spatial diversity by exploiting the fact that the packet is received by multiple receivers.

Multi-rate transmission. A single wireless radio may offer several choices for the link rate transmission. There is a trade-off between the number of hops of a path and the rate selected. Higher rates may lead to increased number of hops. Lower rates may imply fewer hops, but lower packet delivery ratio. The effective selection of wireless link rate by the routing protocol may lead to much better performance.

Multiple radios. To cope with bandwidth limitations, a WMR router, as routers in wired networks, is often equipped with multiple interfaces. Appropriate channel assignment and antenna selection allow exploiting this feature in WMNs. Furthermore, a multi-interface WMR may be potentially equipped with multiple technology-diverse radios, with the consequent heterogeneous characteristics in terms of coverage and rate. This may increase the flexibility of the routing protocol, potentially increasing the routing alternatives.

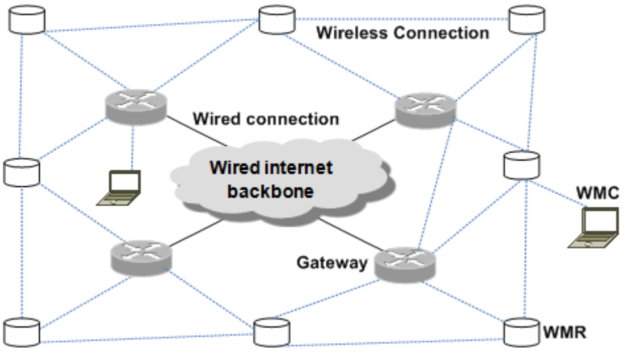

Figure 1. WMN Architecture.

Multiple channels. An intelligent channel assignment scheme may substantially improve the throughput of the routing protocol. For instance, if WMRs are equipped with multiple radios, the multi-channel feature may allow for concurrent transmissions from the same WMR without interferences, by assigning an orthogonal channel to each interface. In this way, the routing protocol may benefit from multi-channel features to minimize interference.

III. ROUTING IN WMNS: PROPERTIES & CHOICES

As a consequence of the above constraints of WMNs, one may extract a list of desirable properties that a routing protocol should ideally incorporate in its design. They are presented in subsection III.A. Furthermore, there are some choices to be made, which are summarized in subsection III.B, so that these properties are present in a routing protocol. These choices represent current approaches found in the literature. As shown in table I, each potential choice in the design of the routing protocol provides one or more of the desirable properties.

A. Desirable Properties

To deal with the specific constraints of WMNs, a routing protocol oriented to maximize throughput for WMNs should ideally have these main properties:

Bandwidth aggregation. In such a bandwidth-constrained network environment, a routing protocol must exploit the rich multi-hop wireless mesh topology in order to support bandwidth aggregation.

Reliability. As WMNs offer multiple paths, the routing protocol should learn several routes between a source and a destination in order to react to link or WMR node failures.

Distributed operation. Routing control information must be distributed throughout the network.

Low path stretch. The use of the best paths becomes a necessity. What best means depends on the scenario, but often, and due to wireless link instability, the best path is not the shortest path (in number of hops) as in wired networks. Eventually, a path that takes into account the wireless constraints whilst not being very different from the shortest one (i.e. low path stretch) should be provided.

Scalability. A routing protocol must not see its performance substantially affected by an increase neither in the number of nodes nor in the number of interfaces per node.

Low control message overhead. As bandwidth is a scarce resource, a goal of a routing protocol is to reduce the overall overhead injected to the network.

Load balancing. When a path is highly congested, all or part of the traffic may be switched to alternate paths, so as to efficiently utilize network resources.

Wireless-aware decision-taking. The routing layer should be aware of the unpredictable events in the underlying wireless MAC and Physical layers of the wireless network.

B. Choices

Due to the specific properties that routing protocols under consideration may ideally have, there are several strategies that may be incorporated in its design. In other words, there are some major choices to be made when designing a routing protocol targeting high-throughput WMNs. After an extensive reading of the existing literature, we identify the most important approaches that may be integrated as part of a routing scheme. There are two mutually exclusive approaches inherited from classical routing protocols, namely:

Hop-by-hop routing. In Hop-by-hop approaches, all the WMRs share the responsibility of determining the route to a destination, as routing decisions are taken at each hop.

Source routing. In source routing, the source WMR computes and maintains the entire path to a destination.

When focusing on WMNs, there are several strategies (not necessarily exclusive) employed in the design of the routing protocol:

Opportunistic (or anypath) routing. The shared and broadcast nature of wireless links may be seen as a feature rather than a limitation to cope with. For instance, in IEEE 802.11 broadcast mode, a single transmission is sufficient to potentially be received by several WMRs in transmission range. Therefore, the probability of successful reception by any of the WMRs is increased without increasing the number of total transmissions.

An approach usually associated to opportunistic routing is *network coding*. Usually, data has been routed through the network without being manipulated or modified. However, with network coding, the transmitted data may be coded by WMRs and decoded at the destination. A coding operation is usually a combination of packets previously received. Thus, each coded packet contains information about different packets, which allows, in some cases, to avoid hop-by-hop retransmissions.

Multi-rate routing. This approach consists of selecting the more appropriate physical link rate to maximize throughput gains. There is a trade-off between reliability (at low link rates) and throughput (at high rates), which should be optimized.

Overlay routing. Strong similarities exist between P2P overlays and WMNs, like decentralization and self-organization. Due to these similarities, the wireless networking research community has tried to push Distributed Hash Tables (DHTs) from application down to the network level. With respect to the DHT routing geometry, multiple paths are often present between WMRs. The key idea is that underlying DHT geometrical structures may allow finding a good trade-off between state stored at each WMR, path stretch, and overhead introduced in the WMN.

Multi-radio multi-channel routing. The decreasing cost of wireless devices makes adding multiple interfaces more feasible. The addition of multiple radios is, in general, associated to the use of multiple channels in order to support concurrent transmissions, which increases the capacity of wireless networks. Channel assignment techniques may vary the quality of a path due to changes in the level of interference, and hence also in traffic load. Moreover, changes in the topology may generate broken paths. The coordination between routing and channel assignment becomes essential in multi-radio multi-channel networks.

TABLE I.
Specific Properties & Choices

Properties	Choices
Wireless-aware	Multi-radio multi-channel, opportunistic
Bandwidth aggregation	Network coding, overlay, opportunistic, multi-radio multi-channel, multi-rate
Scalability	Overlay, geographic
Path stretch	Overlay, multi-rate
Distributed	Overlay, geographic
Overhead	Overlay, geographic
Reliability	Opportunistic, network coding, multi-rate
Load balancing	Opportunistic, multi-radio multi-channel

Geographic routing. Scalability may be one of the most challenging issues to solve in WMNs. Stateless geographic routing approaches exploit the use of existing positioning techniques, like GPS, to avoid the management of routing tables. To route to any destination, each WMR only relies on position information of its local vicinity, hence decisions are taken based on local information.

Additionally, and common to all previous routing strategies, a component that is always present is some form of routing metric. Metrics can be classified into routing metrics and link quality metrics. A link quality metric quantifies the cost of a link, whilst a routing metric quantifies the cost of a path.

As already mentioned, due to wireless link variability, shortest path routing in terms of number of hops is not the best choice as routing metric. Consequently, routing metrics that are aware of path quality fluctuations are needed.

Given the static nature of WMRs, it is feasible to devote a certain portion of the available wireless bandwidth or other resources to carry out link (or path) quality measurements. They may be either passive (i.e. by using the same data traffic itself) or active (i.e. by injecting additional control traffic). Moreover, and due to wireless link quality variation, active or passive measurements may allow providing the required fine-grained path cost estimation.

IV. TAXONOMY

Most WMN routing proposals presented in this section have a distributed implementation that is used to evaluate the routing protocol. This means that they are experimentally evaluated in a real testbed or, at least, they have a distributed implementation in a network simulator. Thus, the focus is not on theoretically optimal protocols that assume a centralized knowledge of the whole network, but on implementable ones.

After summarizing all potential choices identified in section III, the goal of this section is to provide a taxonomy that reflects how the field of WMN research has used and combined *some* of these choices. After a review of the literature, one may notice that not all of them have been assigned the relevance that would have justified a new branch in the taxonomy (e.g., geographic routing). Specifically, the chosen choices are consequence of some properties present in a WMN. The taxonomy is presented in Figure 2 and developed throughout this section.

The proposed classification is based on how each specific property in a WMN is exploited to maximize throughput gains. As recently presented in [40], the focus, in terms of performance metric to optimize, shifts from connectivity to throughput when moving from ad-hoc to WMNs. Therefore, there are other wireless routing protocols in the literature that are out of the scope of this taxonomy. For instance, those routing protocols solely focused on maintaining connectivity between nodes. As they have not been specifically designed for increasing throughput in WMNs, they do not attain the throughput level of the routing protocols considered in this paper.

As a result, we have classified routing protocols that exploit WMN-specific characteristics, and are oriented to maximize throughput gains into two main approaches (Figure 2).

The first one relies on the joint use of multiple radios and multiple channels. This approach may be further subdivided based on the type of antennas employed, namely directional or omnidirectional. Furthermore, routing protocols using omnidirectional antennas have been further classified as coupled or decoupled depending on how tight is the relationship and dependencies of routing and channel assignment.

The second one is based on exploiting the broadcast nature of the wireless medium. In this approach, the subset of proposals referred to as opportunistic routing have been classified into two subgroups that differ in the relationship between the routing protocol and the selection of the link rate of the wireless cards. In single-rate approaches, the routing protocol does not select the link rate, whilst it does in multi-rate approaches. Furthermore, there is another subset of proposals that also exploits the additional CPU and storage capabilities a WMR provides by using one of the two identified network coding strategies: intra-flow or inter-flow network coding.

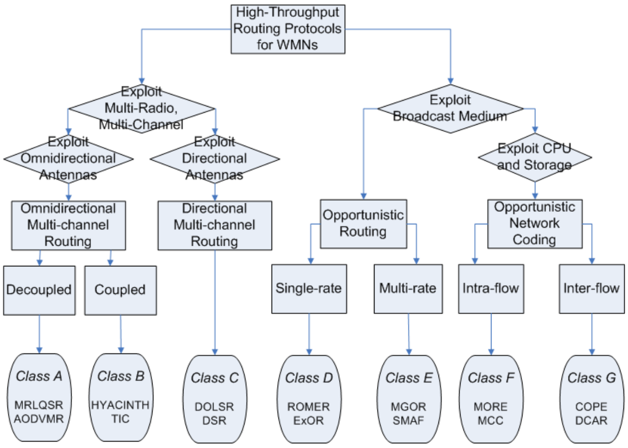

Figure 2. Taxonomy

Previous classifications of routing protocols for WMNs found in the literature ([29], [30]) categorize routing protocols for WMNs based on different criteria than the one used in this paper. On the one hand, authors from [29] classify routing protocols for WMNs based on an architectural component of the routing protocol. More specifically, they categorize routing protocols depending on how they discover and maintain routing paths. On the other hand, [30] classifies routing protocols based on their objectives of performance optimization.

Furthermore, the above literature covers a wider scope of routing, as not all of them were specifically designed for WMNs. For instance, [29] includes protocols initially designed for mobile ad-hoc networks. In [30], routing protocols using the hop count metric are also studied, which do not fully exploit the advantages of WMNs. By contrast, our chosen criterion to classify routing protocols (i.e., what WMN-enabled feature is exploited to maximize throughput), is different from criteria previously used in the literature.

A. Multi-Radio Multi-Channel Routing

The coordinated use of multiple radios and multiple channels per WMR may improve throughput in WMNs. With an intelligent channel assignment scheme, radios can also work at the same frequency band, but tuned to orthogonal channels. The 802.11a, 802.11b/g, and 802.16 standards provide multiple frequency channels, which may provide an efficient use of the available spectrum when appropriately configured to orthogonal channels. As a result, throughput is expected to substantially increase, which is mainly due to the feasibility of transmissions occurring in parallel in multi-radio WMRs and minimization of interference. This is not feasible in a single radio WMR.

Therefore, routing protocols should ideally work in cooperation with a channel assignment scheme. The main goal of a channel assignment strategy is the minimization of interference. On the other hand, the routing protocol determines the paths followed by data packets, and hence the traffic load distribution. In turn, the traffic load distribution determines the interference. Thus, a channel assignment strategy that cooperates with a routing protocol may provide substantial throughput gains.

A WMN offers an ideal architecture for multi-radio multi-channel routing. First, the non-power constrained WMN backbone allows adding multiple radio technologies per WMR. Second, when appropriately configured to orthogonal channels, the addition of radio technologies working even in the same frequency band is no longer an issue. And third, endowing with multiple radios a WMR is economically feasible due to the availability of cheap off-the-shelf commodity hardware.

After a careful review of the literature, one may observe a conceptual difference between proposals that use omnidirectional antennas and those using directional antennas.

1) Multi-Channel Routing with Omnidirectional Antennas

This is the most common approach in the literature. First, omnidirectional antennas are cheaper. Second, due to their radiation pattern, in dense topologies, they may potentially offer increased successful reception probabilities, due to the number of potential receivers in transmission range. However, for the same reason, dealing with omnidirectional antennas can also turn out into increased contention issues without proper medium access coordination.

We have subdivided this group of routing proposals into those coupled and those decoupled with the channel assignment scheme. By coupled channel assignment and routing solution we refer to proposals in which there is a tight relationship between routing and channel assignment. In other words, the routing protocol determines the channel assignment strategy. On the other hand, a decoupled scheme is a multi-radio routing approach that assumes an independent multi-channel assignment strategy in which the assignment is pre-computed.

a) Decoupled Channel Assignment and Routing (Class A)

The routing protocol itself does not have any influence on the channel assignment strategy at all. A simple independent channel assignment strategy to improve throughput is to configure each radio in a WMR to different non-interfering channels. This assumption is made in Multi-Radio Link Quality Source Routing (MR-LQSR) [1] and Multi-Radio Ad-hoc On-Demand Distance Vector (MR-AODV) [3]. Multiple radios are used to increase the number of candidate paths, hence offering more paths with potentially more throughput. They are based on giving higher preference to the more channel diverse path. Giving higher preference to the more channel diverse path may result in a decrease of the contention level between data packets belonging to the same flow traversing a certain path. Moreover, in [2] and [3], addressing the interference from other flows also becomes a concern.

b) Coupled Channel Assignment and Routing (Class B)

In this case, the routing protocol itself determines the dynamics of the channel reassignment strategy. In [11], Raniwala et al. present a routing protocol tightly coupled with a dynamic channel assignment scheme. At a routing level, WMRs build a tree-based topology. Trees are rooted at each gateway of the WMN. WMRs periodically compute a cost metric aimed at joining the less loaded tree. The cost metrics evaluated are the hop count to the gateway, the gateway link capacity, and the gateway path capacity. As a consequence, they may periodically switch between multiple trees, hence providing load balancing among the gateways.

On the other hand, and concerning the channel assignment strategy, each WMR periodically exchanges its channel load within its interference range. Channel usage is estimated by using the number of interfering WMRs and the aggregated traffic load contributed by each WMR. Then, a WMR selects the less loaded channel not currently assigned to a WMR in a higher hierarchy level in a routing tree. It is assumed that traffic load grows as a WMR is higher in the tree hierarchy. Therefore, when assigning channels, a high level WMR has priority over low level WMRs.

As the routing protocol dictates the traffic load distribution and traffic load dynamically changes the channel assignment strategy, the dynamic load-aware channel assignment scheme turns out to be driven by the routing protocol. Furthermore, the tree hierarchy imposed by the routing protocol constrains the channel assignment scheme by determining the channel assignment priorities of WMRs.

Reference [37] presents a Topology and Interference aware Channel assignment architecture (TIC), which describes a hybrid channel assignment technique working in cooperation with a routing protocol based on the Weighted Cumulative Expected Transmission Time (WCETT) [1] metric and the Dijkstra algorithm for minimum path cost computation. It is assumed that each WMR has one radio tuned to the same channel in the same physical layer technology. Furthermore, all these radios have a unique and static channel assigned. The rest of the wireless radios are dynamically assigned.

To assign a channel to each radio, each WMR builds a conflict graph in order to assign orthogonal channels. A conflict graph is used to represent interference between wireless links. Channel assignment and route quality evaluation is done in parallel by combining the use of Dijkstra with the conflict graph. For a source WMR, each non-interfering channel not present in the conflict graph is checked to compute the minimum cost next-hop using WCETT. From all the possible channels and neighbor WMRs, those which minimize the routing cost are chosen. Once the next-hop and channel are determined, the Dijkstra search advances one hop to the intended destination and computes the minimum cost and channel, and so on. Therefore, in this particular case, the channel assignment strategy is determined by the routing protocol.

Additionally, when a WMR changes the channel of one of its radios, data traffic transmitted through this channel switches to the common radio interface. Therefore, the common channel network is used as default network for routing flows until channel assignment in other channels ends. In this sense, the channel assignment scheme also influences routing operation.

2) Multi-Channel Routing with Directional Antennas (Class C)

Directional antennas may significantly simplify the routing protocol. A wireless link composed of two directional antennas is similar in concept to a wired link. In a wired link, there is no interference and it may potentially offer long transmission ranges. In a wireless link composed of directional antennas, especially when there are not many available channels, directional antennas may offer spatial separation to handle contention. Therefore, interference between antennas may be minimized, or totally suppressed. Moreover, directional antennas offer increased transmission range by decreasing the number of hops to reach the destination WMRs. In turn, this decreases the number of medium access contentions.

However, the widespread deployment of directional antennas poses several challenges. On the one hand, automatically-steerable directional antennas are expensive. On the other hand, if they are not steerable, the direction to which the antenna points must be changed manually, which may also be costly.

But this problem is smaller in WMNs, as they have a static WMN backbone. All WMRs and their associated antennas are fixed; hence cheap directional antennas may be located by pointing to a known predefined neighbor.

Routing and channel assignment with cheap directional antennas has been addressed in Directional Optimized Link State Routing (DOLSR) [31]. The WMN is composed of a tree rooted at the gateway. A radio with an omnidirectional antenna, configured to the same channel in every WMR in the network, is used to collect control information. The control information is used to decide which WMR could be the parent in the tree of the WMR. Information gathered from the omnidirectional antenna is used to select the more suitable directional parent. Thus, the directional antennas are used only for data packet transmission. They also evaluate different channel assignment strategies, decoupled from the routing protocol, which is similar to the approaches in [1]-[3].

Reference [33] studies the WMN routing problem when directional and omnidirectional antennas coexist. Essentially, Dynamic Source Routing (DSR) computation is used with a modified version of the Expected Transmission Count (ETX) [41] metric. When a WMR does not have a route to the intended destination, it floods the network by sending control packets that carry the accumulated ETX value. The ETX computation method is modified so that they not only discover neighbors in the omnidirectional range but also in the directional range. Basically, different values of transmission power covering omnidirectional and directional ranges are tested.

B.Opportunistic Routing

Opportunistic routing is based on the following principle: when a WMR wants to transmit a data packet, instead of transmitting it in unicast mode (i.e., to a single next-hop), it directly broadcasts the data packet. The broadcast transmission permits the senders to not necessarily know which WMR is the next-hop. Afterwards, the routing protocol decides on-the-fly which of the potential receivers of the broadcasted packet may forward the data packet, and thus become the next-hop. The potential receivers of the packets need to work in a coordinated way in order to minimize forwarding of duplicated packets. In turn, the forwarding of data packets is also done in broadcast mode. The coordination process entails the need for specific opportunistic routing metrics and mechanisms to decide the best receivers.

Therefore, in opportunistic routing, the next-hop is known after data packet transmission, which is contrary to classical unicast routing approaches. In classical unicast routing approaches, the next-hop is known before the data packet is forwarded. WMNs are a suitable candidate for incorporating the opportunistic routing philosophy. This is because with a dense and static backbone, the number of potential receivers of a broadcast packet increases. Thus, opportunistic routing may provide robustness in the transmission. Specifically, we will focus on opportunistic routing protocols that effectively increase throughput perceived by the destination WMR.

The static WMN backbone offers inherent path diversity. Path diversity is provided due to the existence of a rich mesh topology that also offers point to multipoint links. Thus, opportunistic routing protocols can exploit the point-to-multipoint transmissions a WMN provides in order to maximize throughput gains.

Opportunistic routing tackles a known problem in WMNs, namely short-term path quality variations. An issue in WMNs is to guarantee high throughput paths due to the high variability of the link quality. In general, classical routing protocols are not able to update link costs (and thus not able to update path costs) at the fine time scale wireless link variations occur. They usually re-compute wireless link costs at the scale of various seconds. For instance, the unicast ETX [41] metric is recomputed every 10 seconds. Path recalculation is done at an even coarser time scale. In Opportunistic routing, each packet may potentially follow a different path. Each data packet takes a single path but none of the successive packets are forced to follow this path. There are some possible candidate paths but none of them is chosen a priori. In fact, the path is chosen on-the-fly depending on the current, usually point-to-multipoint, link status.

Furthermore, as transmission is done in a broadcast manner, the transmission rate is significantly improved. This is because, in 802.11, for each data packet transmitted, there is the exponential backoff delay mechanism. For unicast transmissions, this may lead to excessive delays when handling retransmissions.

Moreover, even when the transmission is successfully received, the data packet needs to be acknowledged, not allowing the potential sender to transmit a new data packet until the ACK control packet is received. On the other hand, in broadcast mode, there are neither per-link retransmissions nor acknowledgment procedures. Thus, WMRs may potentially transmit at higher rates, being only limited by the physical carrier sensing. As a consequence, throughput may be increased.

We classify opportunistic routing protocols into two different categories: single-rate and multi-rate. In single-rate opportunistic routing, it is assumed that the WMRs are not able to manage the data rate at which packets are transmitted. On the other hand, in an opportunistic multi-rate environment, the routing protocol selects both the forwarding next-hop and the data rate for each radio in the WMR.

1) Single Rate Opportunistic Routing (Class D)

The main issue in these protocols is how to decide which neighbors forward data packets. The main challenge that arises is the cooperation between the potential next-hop set in order to select the best forwarding WMR, where *best* often means the WMR that maximizes throughput gains.

Extremely Opportunistic Routing (ExOR) [16] computes at each potential forwarder the shortest path to the intended destination. The shortest path is estimated by summing up the link costs associated to the path calculated using the Dijkstra algorithm. The link costs are computed using the ETX [41] metric. Thus, each WMR has all the ETX values to reach the destination and it calculates the minimum ETX value. For coordination purposes, a forwarder priority list is sent in each data packet to schedule the order of forwarding attempts by the next-hop set. As a result, a WMR only forwards a data packet if all higher priority WMRs failed to do so.

In Resilient Opportunistic Mesh Routing (ROMER) [15], the key idea is that each packet carries a credit which is initially set by the source and is reduced as the packet traverses the network. As in ExOR, each WMR also computes a path cost for forwarding a packet from itself to the intended destination.

In ROMER, a data packet may be duplicated when traversing the WMN. This may happen because potential next-hops may forward data packets if the credit of the packet is high enough. The credit associated to each data packet is decremented at each forwarding step according to the WMR credit cost, which basically means that more credits are consumed as the packet moves away from the shortest path to the destination; hence data packets are not forwarded through these paths.

2) *Multi-Rate Opportunistic Routing (Class E)*

Leveraging rate control to select the optimal rate in opportunistic routing may lead to throughput gains. Specifically, some broadcast links may be underutilized, hence losing throughput. A potential improvement driven by the routing protocol consists of increasing the data rate to increase throughput, and hence the optimal utilization. (Note that this is independent from MAC layer auto-rate algorithms based on unicast MAC layer procedures, not compatible with opportunistic routing, such as counting the number of retries per packet to determine the optimal rate.)

On the other hand, as higher transmission rates entail shorter radio ranges, link loss rate may potentially be increased. Therefore, the network could eventually become disconnected. A solution for these links is to decrease the link rate of the WMR, thus increasing the number of potential next-hops (i.e., increasing connectivity).

Nevertheless, achieving the optimal rate poses several challenges. To date, there are some recent proposals addressing multi-rate. First, as different rates mean different transmission ranges, there is a trade-off between the rate selected and the number of hops. Choosing a high rate may decrease reliability, thus requiring more data packet (re-)transmissions. A low bit rate may guarantee reliability, but it may also result in an unnecessary decrease of throughput. Therefore, depending on the bit rate selected, the set of potential next-hops of a WMR is variable.

Zeng et al. [24] propose Multirate Geographic Opportunistic Routing (MGOR), a heuristic for opportunistic multi-rate routing, which takes into account the constraints imposed by transmission conflicts. They argue that the problem is NP-hard, and so heuristics are used to find a solution. Specifically, two different heuristics are proposed. One is Expected Advancement Rate (EAR), which addresses what next-hop is closer to the destination in distance by using location information. The other heuristic is Expected Medium Time (EMT), which is based on a generalization of ETT [1].

On the other hand, Shortest Multirate Anypath Forwaring (SMAF) [19] computes the opportunistic multi-rate path by modifying a generalized version of the Dijkstra algorithm. The main contribution consists of reducing the number of neighbor combinations to test for finding the optimal next-hop neighbor set at a given rate. Specifically, the optimization is based on testing a number of combinations equal to the number of neighbors, and not all the possible combinations for each tested rate, which is an exponential number of combinations. This is the key to achieve a polynomial algorithm, hence reducing computational complexity.

C. Opportunistic Network Coding Routing

In the reviewed routing schemes, network coding is an add-on to opportunistic routing. But it is classified as a different group in the taxonomy, due to the qualitative conceptual change that exploiting the CPU and storage of WMRs may entail.

Essentially, in opportunistic network coding routing, WMRs mix the content of data packets. Then, at each hop, they transmit in a broadcast manner the resulting coded packet over the point-to-multipoint wireless medium. Therefore, every coded data packet received at an intended destination contains information about different original packets. Different received data packets contain information of some original packets, thus providing, in general, useful incremental information to the receiver. Additionally, network coding may employ, if needed, original non-previously coded packets received at the destination.

Luckily, network coding poses specific requirements that may be easily fulfilled by WMN backbone nodes. First, WMRs need to keep remarkable state information to store data packets. Second, for some network coding scenarios, each WMR is recommended to be highly static in order to facilitate the buffering of data packets to be combined. Finally, WMRs require considerable CPU operations for mixing packets. As a consequence, WMRs should not be power-constrained. We have grouped network coding routing into two main groups: intra-flow network coding and inter-flow network coding.

1) *Intra-Flow Network Coding (Class F)*

Intra-flow network coding is based on mixing packets belonging to the same data flow. This is, in fact, a specific case of single-rate opportunistic routing. When a source wants to send data packets to a destination, the source WMR breaks up the file into batches of packets and keeps transmitting packets in broadcast mode from the same batch until the batch is acknowledged by the destination. However, in intra-flow network coding, there is no coordination between the receivers of data packets.

Before forwarding data packets, the forwarders store them in a buffer. When enough data packets are stored, the forwarder computes a random linear combination of the packets. The mixed packets are headed to the same destination. The randomness in the mixing procedure assures with high probability that different WMRs will not forward exactly the same packets. Thus, the number of packets received by the destination is increased. It is likely that WMRs participating in the forwarding procedure send different combinations of packets.

In MAC-independent Opportunistic Routing & Encoding (MORE) [14], every WMR sends probe packets to capture the link costs associated to its neighbors. Upon link calculation, the cost of each link is flooded to the whole network so that the Dijkstra algorithm can calculate the shortest paths. The cost associated to each link is calculated by means of the ETX [41] metric. The WMRs check whether they are closer to the destination than the transmitter or not by using Dijkstra combined with ETX. If this is the case, they store the received coded packets in a buffer. When a forwarder has sufficient data packets, it makes a random linear combination of received data packets, thus generating new coded data packets, and it eventually forwards the coded packets. This process continues at each hop until enough data packets are received by the destination so that it is able to decode the original information. In order to decode the original data packets, a common constraint for the receiver is that the number of innovative coded data packets received must be greater or equal to the number of original data packets. Furthermore, to support reliability, the destination WMR sends and ACK (using unicast best path routing based on ETX) to the source when it has received enough coded data packets.

Gkantsidis et al. present Multipath Code Casting (MCC) in [39], which also employs intra-flow network coding. However, in this scheme, link costs are collected and propagated by an overlay routing discovery module called Virtual Ring Routing (VRR) [13]. Moreover, a credit-based distributed algorithm is used for rate control. And, backpressure theory ideas are used in order to avoid congestion and keep the length of each WMR queue bounded.

2) *Inter-Flow Network Coding (Class G)*

In inter-flow network coding, the coding operation is done over data packets belonging to different data flows. Coding Opportunistically (COPE) [16] is based on mixing packets generated by different flows when a WMR detects an advantage for doing this operation. An advantage is usually detected when the number of coded packets transmitted in a single transmission may be maximized and the destination has enough information to decode the packet. To detect an advantage, a WMR has to gather some information of the flows present in the network. In COPE, Dijkstra and ETX [41] are used for computing minimum cost paths.

Distributed Coding-Aware Routing (DCAR) [35] goes beyond COPE and suggests combining the route discovery process with the detection of coding opportunities in order to maximize the inter-flow network coding opportunities. On-demand source computation combined with the ETT metric are used for calculating minimum cost paths. The basic idea of this scheme is to discover intersecting paths, instead of choosing disjoint paths for certain flows in the network. These flows are such that making them coinciding in a WMR to code their packets is beneficial for achieving network throughput gains. Thus, end-to-end throughput of different flows is maximized.

V. DESIGN BUILDING BLOCKS

The functionality required by a high-throughput routing protocol may be split into three building blocks, namely neighbor discovery, control message propagation, and route determination. These building blocks are common to the broad set of network protocols studied in the previous section.

Essentially, every building block addresses one specific function, which is a part of the routing protocol. First, WMRs have to gather link cost information about its neighbors (i.e., neighbor discovery).

Second, information about link costs must be distributed throughout the network to the appropriate WMRs, implying a certain propagation of route control messages over the WMN. This is handled by the control message propagation building block. Finally, once the necessary routing information is collected by all parties, the routing paths to the destination nodes are determined (i.e., route determination).

Notice also that the characteristics of WMNs highly influence the strategy adopted by each building block to carry out its function. Throughout this section, the different underlying strategies and their inter-dependency with the exploited characteristics are studied for each identified building block. In brief, in neighbor discovery, the radiation pattern of the antennas; in control message propagation, the stable non-power constrained backbone; and in route determination, the forwarding approach employed and the possibility of employing multi-rate features. Moreover, open issues related to each building block are also discussed.

A. Neighbor Discovery

The neighbor discovery building block groups the functionality related to the process of determining which WMRs can be reached by means of direct communication (i.e., without having to cross any other intermediate WMR). Periodic or non-periodic broadcast packets are usually used to discover the WMRs reachable by direct communication. This could be sufficient to maintain a neighbor table in each WMR if wireless links were as stable as wired links. However, in wireless links, the neighboring relationship is mainly determined by the quality of the link. As it is highly variable and unstable, the wireless link quality is not limited to the same two classical states as in wired networks. In classical wired networks, it is usually assumed that a link works well or does not work at all. Moreover, wireless link quality may vary depending on the direction of the link, which results in wireless link asymmetry. In practice, this means that the neighbor discovery building block is in charge not only of discovering WMRs in the physical proximity, but also of estimating the quality and stability of a link towards each WMR within transmission range. Depending on this latter estimation, a neighboring relationship will be established or not.

WMNs offer an environment that enables accurate wireless link estimation. A basic approach would send a control packet and then wait for an answer. However, the non-power constrained nature of WMNs allows implementing more elaborate and complex procedures to increase the wireless link cost estimation accuracy. On the other hand, in WMNs, the radiation pattern of the antennas equipping WMRs may cause considerable changes in the issues tackled to measure link quality.

Therefore, link quality measurement procedures and their associated link quality metrics, taking into account the antenna radiation pattern, become key issues of the neighbor discovery building block. Link quality metrics are explained in the first subsection. The second subsection summarizes the different procedures to carry out depending on the antenna radiation pattern.

1) Link Quality Metrics

The cost associated to each link, which will be later used to calculate the routes in the route determination building block, requires the computation of link quality metrics in the neighbor discovery building block. Note that link metrics are conceptually different from routing metrics. As mentioned in section II, link quality metrics quantify the cost associated to a wireless link, and they are handled by the neighbor discovery process. On the other hand, routing metrics are handled by the route determination building block, as they measure the quality of paths, and not merely of single links. Thus, routing metrics are built by using link metrics as input to quantify the cost of an end-to-end route path.

As shown in table II, for each of the proposals found in the literature, two main factors condition the design of wireless link metrics: the primary metric employed and the measurement technique utilized to calculate the parameters to estimate. Besides, the procedure may vary depending on the radiation pattern of the antenna. Finally, the link cost to be used by the route determination building block (referred to as metric in table II) is also presented.

Primary metric. A primary metric is an indicator used to quantify the quality that a wireless link includes. There are four primary metrics [12] used in the literature, namely:

Packet delivery ratio (PDR): The more common parameter chosen in the literature (e.g., [1]- [5], [37], and [41]) quantifies wireless link reliability at a packet level. The PDR is the ratio of packets correctly received/captured to the total number of packets sent by the sender. The PDR is usually calculated in both directions of a wireless link in order to deal with *link asymmetry*, which is common in wireless links.

Bit error rate (BER): This is the ratio of bits with errors to the total number of bits that have been received during a given time period. The BER primary metric defines the reliability at a bit level.

Signal-to-interference plus noise ratio (SINR): The extent to which the power of the received signal exceeds the sum of noise plus interference at the receiver. SINR quantifies the quality of the received signal.

Received signal strength indication (RSSI): This is the signal strength observed at the receiver's antenna during packet reception. RSSI defines the quality of the signal received.

Measurement technique. The most common measurement technique used to measure packet delivery ratio is based on the probe packet concept.

Probe packet: It consists of periodically broadcasting or unicasting a packet of fixed size. The packet contains the number of probe packets received by the sender. Therefore, the receiver of the probe packet can calculate the delivery ratio of the link in the receiver-to-sender direction.

Packet pair: Packet Pairs are a special case of probe packets. In ETT [1], Metric of Interference and Channel-Switching (MIC) [2], and Interference-Aware Metric (iAWARE) [3], a WMR sends two unicast probe packets of different size. The receiver WMR measures the difference between the instants in which each packet is received, and it forwards this information to the sender. Then, it is used to estimate the available bandwidth of a link.

Furthermore, based on the strategy employed to generate probing packets, the approaches followed may be categorized as active, passive and cooperative.

Active: A WMR explicitly sends control packets to discover its neighbors. This is the default procedure in most proposals explored, either sending probe packets or packet pairs.

Passive: In Efficient and Accurate link-quality monitoR (EAR) [5], discovery can be made with the use of data packets. The real traffic generated in the network is also used as probing packets without incurring extra-overhead.

Cooperative: In [5], a WMR overhears data packets transmitted by each of its neighbors to estimate the link quality from its neighbors to itself.

TABLE II.
Link Quality Estimators

Proposal	**Antenna**	**Primary metric**	**Measurement technique**	**Link Quality Estimates**
ETX[41]	Omni/dir	PDR	Probe packet	Loss rate
ETT[1]	Omni/dir	PDR	Packet pair	Bandwidth
mETX[4]	Omni/dir	BER,PDR	Probe packet	Loss rate
EAR[5]	Omni/dir	PDR	Probe packet passive cooperative	Bandwidth
Power-ETX[33]	Omni/dir	PDR	active	Loss rate
MIC[2]	Omni	PDR	Packet pair	Bandwidth Interference
iAWARE[3]	Omni	SNR/SINR PDR	Packet pair	Bandwidth Interference
ETP[38]	Omni	PDR	Probe packet	Bandwidth Interference

Link Quality Estimates. The final goal of the measurement procedure is to quantify the link cost by means of one or more link quality estimates, which are obtained by appropriately combining one or more wireless link primary metrics. The metrics found in the literature reviewed follow:

Loss Rate: Most of the proposals try to measure the loss rate which is the percentage of packet/bit losses in the link. The loss rate is usually measured by means of probe packets, which are used to calculate the PDR primary metric. The values obtained for the PDR primary metric are used to compute the packet loss rate. For instance, these values may be averaged by means of an exponentially weighted moving average (EWMA). In [33], a modification of the ETX metric (Power-ETX) is proposed to deal with a WMN composed by WMRs equipped with omnidirectional and directional antennas. It is based on alternating the transmission of broadcast probe packets at two different transmission power levels. Each of these transmission powers covers the omnidirectional and directional range. As a result, a WMR may discover neighbors that are beyond the omnidirectional range, which are neighbors in the directional range.

On the other hand, modified ETX (mETX) [4] takes into account the average and standard deviation of the BER primary metric of the captured packets to calculate loss rate. The standard deviation may potentially be useful in order to quantify wireless link variability.

Bandwidth: There are proposals ([1]-[5], and [38]) focused on measuring the available bandwidth of the wireless link. Available bandwidth is usually captured through the use of packet pairs.

Interference: Interference caused by neighbors of a WMR in transmission range, may also be a parameter to estimate. Specifically, the interference measured is interflow-interference. This is interference generated to each other by/to packets belonging to different flows. Essentially, to measure the interflow-interference ([2], [3], and [38]), monitoring methods are employed to capture the number of interfering WMRs at each wireless link. In general, this estimate is associated to the use of omnidirectional antennas.

Measurement techniques introduced by omnidirectional antennas are based on sensing the medium and exchanging the captured information. For instance, in [2], a rough estimation is made to count the number of interfering neighbors of a WMR. On the other hand, [3] uses the measured SNR and SINR primary metrics to capture inter-flow interference variations.

2) Dependency of Neighbor Discovery on the radiation pattern of the antennas

The procedures followed to perform neighbor discovery vary depending on the radiation pattern of the antennas equipping WMRs. According to their radiation pattern, antennas can be classified into directional and omnidirectional.

a) Omnidirectional Antennas

An omnidirectional antenna has a uniform radiation pattern in all directions. The discovery of neighbors with omnidirectional antennas becomes straightforward with the use of broadcast probe packets [41].

On the other hand, interference requires special attention, as studied in [1]-[3], and [38]. For instance, in high-density WMNs, where WMRs are equipped with omnidirectional antennas, contention should be carefully handled due to the potentially high number of neighboring WMRs.

b) Directional Antennas

Neighbor discovery with directional antennas is more challenging, since it introduces additional issues with respect to neighbor discovery with omnidirectional antennas. With directional antennas, WMRs must appropriately manage the direction and beam width of the antennas in order to maintain their neighbors. On the other hand, non-steerable antennas must be manually installed.

When direction and beam width of the antennas are correctly managed, the deafness problem may be minimized. Deafness occurs when a transmitter is unable to communicate with its intended receiver, because the antenna of the receiver is not pointing to the transmitter. To discover the neighbors of a WMR, some approaches have been proposed:

Probabilistic discovery: In [32], probe packets are sent in a random direction and beam width, to calculate the direction and beam width of the antenna.

Omnidirectional neighbor discovery: As stated in [31], omnidirectional antennas could be used to handle control messages for directional antennas. Specifically, omnidirectional antennas are used to discover the neighbors of directional antennas and estimate their associated wireless link costs.

Link quality metrics with directional antennas may be simplified with respect to the link quality metrics for omnidirectional antennas. Directional antennas increase spatial separation for contending transmissions compared to contention in omnidirectional antennas. Therefore, estimates that quantify interference may not be necessary, as presented in table II. An appropriate channel assignment scheme offering frequency separation may be sufficient to deal with contention in scenarios with directional antennas. Therefore, as shown in table II, link quality interference estimates may not be totally necessary. In principle, proposals, such as [41], may be directly employed with directional antennas. However, due to their different physical layer properties, link metrics should be slightly modified, as detailed in previous subsection [33].

OPEN RESEACH ISSUES

A list of the identified open research issues related to the neighbor discovery building block follows:

Link quality. Vlavianos et al. [12] suggest that every single primary metric on its own may not be a good estimate of link quality. A proof of this fact in an indoor testbed may be found in [12]. These studies showed that although BER may be a good predictor, it requires a high number of computations to make the appropriate measurements. On the other hand, RSSI cannot capture interference and SINR is quite complex to be measured. A starting point may be a deep review of the effects captured by each of the different primary metrics by studying appropriate combinations of the primary metrics in order to find an accurate link quality metric.

Control overhead vs network resources. When designing a new wireless link metric proposal, there is a trade-off between the control overhead devoted to measure link quality with enough accuracy and the network resources consumed. Most current work is devoted to send control packets that contend with data packets, and thus affect the behavior of the network. This may be solved by applying passive measurement strategies. However, an in-depth analysis providing accuracy bounds of these techniques may be required.

Active measurement strategies. Regarding active measurements, the schemes followed by recent literature are quite similar. Active measurement techniques are based on periodically sending broadcast or unicast probe packets. An effort should be made to study other measurement strategies. For instance, in general, the size of the probe packet and the inter-generation time of probe packets are fixed. A future research direction may consist of evaluating whether changes in the active measurement strategy may lead to more accurate link quality metrics.

Self-interference: Active probe packets have the disadvantage of affecting the wireless link quality they are measuring. Current wireless link metrics do not take into account the interference generated by the active measurements. A detailed study of the impact of interference caused by active measurements may be of interest.

Wireless link quality prediction. A parameter not sufficiently evaluated in current work on wireless link quality assessment is how to predict the variability of a wireless link. Keeping historical measurements or storing traffic patterns to predict the future state of a link may provide a starting point.

Link quality estimation with directional antennas. The spatial separation offered by directional antennas is able to decrease the complexity on the calculation of a link metric. However, directional antennas have their own physical layer properties. A subject of further study may be the definition of estimators specific to directional antennas rather than using those originally designed for omnidirectional antennas.

B. *Control Message Propagation*

The control message propagation building block is responsible for sending all the necessary routing control messages to the appropriate WMRs.

The cost incurred by the transmission of control messages is not as critical as in power-constrained ad-hoc networks. As a consequence, an appropriate control message propagation building block for WMNs should be aimed at maximizing overall throughput by propagating accurate routing information of wireless link measurements, even at the expense of being more costly. On the other hand, a secondary goal is to decrease the overall overhead incurred by the building block. In this sense, as WMNs offer a stable backbone, no additional control messages due to the movement of nodes must be sent.

In WMNs, the literature distinguishes between two different traffic pattern scenarios: 1) traffic only exchanged between WMRs and gateways, and 2) traffic exchanged between any pair of WMRs. Throughout this section, we refer to the former as any-to-gateway and the later as any-to-any. References [11], [31], and [38] assume the any-to-gateway scenario. References [6]-[10], [13], and [26] assume the any-to-any scenario.

Furthermore, in WMNs, both traffic scenarios have in common the use of some strategy to perform the propagation of route control messages. Depending on the particular protocol, control message propagation could be carried out by one (or both) of two components: route dissemination and route discovery. Their common goal is to provide the necessary route control information to the route determination building block. And the potential coexistence of route discovery with route dissemination is facilitated by the stability of the WMN backbone. This is explained in the first subsection. On the other hand, depending on the combination between route dissemination and discovery, different techniques are presented in the literature to efficiently propagate control messages. They are discussed in the second subsection.

1) Route Dissemination & Route Discovery

The goal of route dissemination and route discovery approaches is the same, i.e., obtaining the necessary routing information from the network to compute the routes, but the way in which they obtain such information is different.

Route dissemination refers to the process of propagating information about link state previously obtained by the neighbor discovery building block. And, this information is periodically disseminated to the network in a proactive way, i.e., without any WMR asking for it. There are some key design decisions to make, such as the accuracy of the information to disseminate. For instance, in [6] the accuracy of the information disseminated is decreased as the distance in hops from the disseminator to the recipient WMR increases.

In addition, there is another method for obtaining routing information from WMRs in a WMN, which is the route discovery process. It is triggered by a source WMR for obtaining the necessary routing information on-demand. Therefore, it is done in a reactive way, that is, when the source WMR has data packets to send to a certain destination. In brief, this process usually works by sending control messages that asks for route information to the WMRs they traverse. Once these control messages obtain the requested routing information, they are sent back to the requesting WMR.

In WMNs, the route dissemination and route discovery components may need to work in cooperation. In other words, both components may complement each other. For instance, in large WMNs, route discovery may help route dissemination to complete the propagation of required route control information, as it is not practical in this case that all WMRs keep state about the rest of the WMRs in the network. Therefore, the existence of route discovery may be highly dependent on the procedure followed for route dissemination and the other way around.

The stability of the WMN backbone facilitates the coexistence of both route dissemination and discovery components. For instance, one may employ a set of well known (i.e., by all WMRs) static WMRs to which all routing information is disseminated. As this set of WMRs is not mobile, it facilitates any WMR requester to locate/access them.

Nevertheless, in some cases, route dissemination may be sufficient to obtain the necessary routes. For instance, in small WMNs, a flooding-based dissemination scheme may be appropriate. In this case, each WMR in the network has enough information to route packets to any destination without incurring into excessive overhead due to the small size of the WMN. Furthermore, depending on certain WMN requirements (e.g., delay), the route discovery process may be sufficient to obtain the desired routes.

2) *Techniques for Propagating Control Messages*

Route dissemination and route discovery require a massive transmission of control messages throughout the network. Therefore, it is fundamental that this is done as efficiently as possible. In this subsection, we present a brief review of representative methods for propagating routing control messages.

Every routing protocol may have an associated technique for propagating useful control messages over the network. Table III presents a summary of this section. We have categorized control message propagation schemes as tree-based, efficient flooding, and all-to-some propagation. Moreover, the components (dissemination and/or discovery) used to gather routing information for each studied proposal are also presented. Finally, the traffic pattern scenario assumed by each proposal is also shown.

A discussion of each of the propagation schemes follows.

Tree-based: Several approaches in the literature are based on tree topologies ([11], and [38]). Such a tree structure is used in any-to-gateway scenarios.

Essentially, the root of the tree is a gateway in the WMN. Thus, as many trees as gateways are built. These trees are usually built in an incremental way, i.e., they are expanded as WMRs join the network. If there are multiple trees, a recently joined WMR must decide which tree to join.

The construction and maintenance of a tree topology determines specific control message propagation strategies. In MAC-Aware Load Balancing (MaLB) [38], each WMR disseminates the accumulated routing information to its parent WMR. Specifically, each WMR propagates to its parent the cumulative routing information of all the WMRs for which it is root of the subtree that includes all WMRs from leaf WMRs up to itself. On the other hand, in [11], the gateway disseminates its routing information to the rest of the WMRs in the tree following the tree-like structure. Moreover, there is a route discovery component that requests to the gateway, which is the root of the tree, if a new WMR is allowed to join the tree. Then, the gateway sends an answer to the new WMR.

TABLE III.
Approaches to Send Control Messages

Proposal	**Scenario**	**Components**	**Strategy**
Clustering[26]	Any-to-any	Dissemination	Efficient flooding
Fisheye[6]	Any-to-any	Dissemination	Efficient flooding
LOLS[7]	Any-to-any	Dissemination	Efficient flooding
OLSR[8]	Any-to-any	Dissemination	Efficient-flooding
Gossip[17]	Any-to-any	Dissemination	Efficient-flooding
ORRP[9]	Any-to-any	Dissemination Discovery	All-to-some
VRR[13]	Any-to-any	Dissemination Discovery	All-to-some
Hyancinth[11]	Any-to-gw	Dissemination Discovery	Tree
MaLB[38]	Any-to-gw	Dissemination	Tree

In both above approaches, the control message propagation is influenced by the tree topology. Specifically, the propagation of control messages in tree-based proposals is such that leaf WMRs do not forward control messages.

Efficient flooding: Flooding is a well-known technique to propagate messages to all the WMRs in the network. A WMR disseminates (i.e., route dissemination component) a message to all its neighbors and these neighbors, in turn, transmit to all of its neighbors, and so on, until all the WMRs receive the message. However, this may incur in unnecessary duplicated transmission of packets. To avoid reception of duplicated packets, [8] proposes to use the multipoint relay scheme. This strategy is based on acquiring 2-hop neighbor information in order to select the minimum number of 1-hop neighbors that guarantee successful reception of all 2-hop neighbors.

On the other hand, the scheme presented in [17], follows a gossip-based approach, in which each receiver decides with a certain probability if the control message is forwarded or not. Essentially, a source WMR sends a control messages with probability one. A WMR forwards a control message with probability p and discards the control message with probability 1-p. If a WMR receives a previously received control packet again, it is discarded.

Although not specifically studied for WMNs, clustering [26] could potentially be another strategy employed to reduce the overhead caused by route control messages. Clustering is based on partitioning the network into groups of WMRs called clusters. The forwarding of control messages is limited to cluster heads and cluster gateways. A cluster head is chosen so that all WMRs in the cluster receive control messages. A certain WMR is elected as cluster gateway to forward route control messages to other clusters. In this scheme, additional route control messages to elect the cluster head as well as the gateways must be sent to build the clusters.

A specific case in efficient flooding approaches is partial-flooding approaches. In [6], the flooding process only covers a certain area of the network close to the source WMR. Besides, the flooding may be done at different frequencies depending on the range covered. In fact, there are some strategies focused on reducing the frequency of flooded messages. One approach proposed in [6] is to define different frequencies of transmissions depending on the distance in number of hops from the disseminator WMR. Thus, the more distance, the less frequently routing information is disseminated. Adidtionally, the disseminated information may vary depending on the dissemination period. In Localized On-demand Link State (LOLS) [7], for short periods, each WMR sends route control information which quantifies average values of link costs. This route information is sent to the entire network. On the other hand, for longer periods, WMRs disseminate route control information which quantifies current link cost to WMRs in the neighborhood.

All-to-some: In an all-to-some approach, all WMRs maintain routing entries to some WMRs. The routing information stored in each WMR differs. The goal is to keep routes to a sufficient number of WMRs in the WMN so that it is guaranteed that any intended destination is reachable. These proposals pose several advantages. For instance, there is no flooding process involved. And opposed to flooding-based approaches, route state information stored at each WMR is substantially reduced. To obtain the routing information, some proposals based on sending the requests in some strategically pre-determined directions have been conceived ([9], and [13]).

A representative example of all-to-some schemes is VRR [13]. In fact, VRR explores the idea of porting overlay routing concepts, usually used at Application layer, to sit directly above the MAC layer. An overlay is basically a routing structure that relies in an underlying network routing protocol. Specifically, VRR employs a ring-like structure. Every WMR maintains paths only for their virtual neighbors, which are some predecessors and successors in the ring structure. Virtual neighbors may be separated in the physical network, hence requiring multi-hop paths to reach each other. Thus, a virtual hop may be composed of multiple physical hops. VRR exploits this dichotomy to assure that following the virtual paths is sufficient to reach any intended WMR. To build these virtual paths, a request (route discovery) is sent to find the WMRs that are virtually closest to the requester in the ring structure. Furthermore, the request includes routing information about the requester (route dissemination) in order to update routing information at the requested WMRs.

In Orthogonal Rendezvous Routing Protocol (ORRP) [9], a request (route discovery) is sent in orthogonal directions until it finds a WMR with the route information requested. Furthermore, each WMR periodically disseminates (route dissemination) its routing information in two orthogonal directions. Thus, the number of control messages in the network is decreased compared to a flooding approach by sending control messages to only two orthogonal directions. This strategy is based on the idea that two pairs of orthogonal lines intersect in a plane.

OPEN RESEARCH ISSUES

A list of the identified open research issues related to the control message propagation building block follows:

Propagated information. Given the instability of wireless links, a challenge that arises is what exact information is going to be spread to other WMRs in the WMN. For instance, one possible option is to associate a predicted lifetime to the propagated wireless link cost. This may be calculated by the neighbor discovery building block.

Intelligent dissemination. Future work should also target the minimization of the routing overhead. For instance, one may consider an intelligent strategy that only disseminates routing control messages when relevant changes occur. A question that arises here is what is considered as a relevant change in a WMN. There is a proposal for generic networks (i.e., not only WMNs) suggesting this possibility in [10].

Route dissemination vs route discovery. There is no generic agreement in the procedure to carry out to propagate route control messages. Although route discovery may exist, it is not clear its relative importance with respect to route dissemination. The route dissemination component may yield lower delays but considerable overheads costs. On the other hand, the route discovery component may lead to higher delays but lower overhead costs. Probably, the trade-off between delay and overhead may depend on the WMN requirements which may dynamically change. As a result, the importance between route dissemination and discovery may ideally vary over time. Therefore, the introduction of mechanisms devoted to gather dynamic WMN requirements so that the relation between these components is optimal may be a subject of further study.

Paths with enough available bandwidth. In general, the studied routing protocols globally assume that there is a path with enough available bandwidth to the destination. However, when there is not enough bandwidth available to later send the data packets, path discovery should be avoided. In WMNs, it is usually assumed that there is a path between any pair of WMRs. But even though there is a path, it is not guaranteed that there is sufficient available bandwidth to maintain a communication. The introduction of route discovery or dissemination mechanisms that provide path reservation may be of potential interest. For instance, this may be done within the control message propagation building block by marking reserved nodes, hence avoiding their participation in other potential paths.

Overlays. A promising approach for efficient control message propagation is the use of overlays for propagating routes. However, there is a primary challenge to face. In fact, porting P2P overlay routing systems to the network layer is not trivial, as there are some differences to take into account. First, pushing Distributed Hash Tables (DHTs) on top of the link layer makes connectivity between any couple of WMRs become an issue. And second, the mapping of logical paths of P2P structures into physical paths does not take into account the underlying physical topology, which leads to path inefficiencies. In general, this is not a problem in wired networks, due to their higher link rates. However, this is no longer true in WMNs where bandwidth is a scarce resource. Consequently, the study of strategies able to generate logical paths that are similar to physical paths may be of potential interest. For instance, this may potentially be done by setting up some rules to apply when a WMR joins a WMN, so that its assigned location maintains the logical structure without compromising the path stretch of the WMN.

C. Route Determination

Based on the routing information (e.g., link cost information) gathered by means of the control message propagation building block, the route determination building block is in charge of determining the most appropriate routing paths from a certain WMR to any other WMR (any-to-any scenarios) or from/to the gateway (any-to-gateway scenarios). Thus, the expected outcome of the route determination building block is the computation of routing tables that specify the next-hop for incoming data packets. Furthermore, to compute routing tables in WMNs, it is necessary to take into account the different methods incoming data packets may be forwarded.

As a result, the route determination building block depends on two main components, namely forwarding approach and route computation. The particular properties of a WMN allow a WMR to forward data packets using different approaches (i.e., unicast and broadcast), which are explained in the first subsection. The different forwarding approaches have several implications in the route computation design, which is introduced in the second subsection. Specifically, the forwarding approach has several implications on the algorithms employed to compute the routing tables. These algorithms determine the path that has the minimum route cost metric to the intended destination. Additionally, the routing metric design depends on the utilized forwarding approach. (A routing metric is used to quantify the cost of the paths to the intended destination.)

1) Forwarding Approach

In WMNs, there are two methods for forwarding data traffic through the network to the next-hop. On the one side, there exists the option of deterministically unicasting the data packet from one WMR to one of its neighbors, which is selected by looking up the pre-computed routing table. On the other side, one may broadcast from one WMR to all WMRs in transmission range. Therefore, in a broadcast forwarding approach, various WMRs may potentially be the simultaneous receivers of a data packet.

The unicast approach handles the wireless link in the same way forwarding in wired networks does, i.e., as if it was a point-to-point wired link. A directional or omnidirectional antenna may potentially be used in WMRs following the unicast approach. However, for environments where direction of data packets is known and unique, it may be more efficient to associate a directional antenna with the unicast forwarding approach.

On the other hand, the broadcast approach, changes the classical concept of link. In a shared wireless medium, transmission matches a point-to-multipoint distribution rather than a point-to-point one. Thus, omnidirectional antennas are specially suited to exploit such kind of links, where may be useful to send data packet in all possible directions and/or received by multiple next-hops.

2) Route Computation

A static and non power-constrained WMR can perform costly route computations which is not feasible for nodes belonging to power-constrained wireless networks. Therefore, a WMR may, in general, use shortest-path algorithms to calculate the more appropriate routing paths without taking into account battery or CPU-load issues.

The algorithms to compute the minimum path cost to the intended destination can be categorized as Dijkstra, Bellman-Ford, and local-based.

Dijkstra: In link state routing approaches, the link costs of the entire network are disseminated by using an adequate strategy to propagate control messages to the intended receiver. In this approach, the algorithm to compute the shortest path commonly used in WMNs is based on modifications of the well-known Dijkstra algorithm.

Bellman-Ford: In Bellman-Ford-based routing protocols, routes are computed in a more distributed manner. In this case, a WMR receives information about the network after being processed by its neighbors. The distance-vector approach is used. There are various flavors of the Bellman-Ford algorithm. For instance, one of these flavors is used in on-demand source routing to update the path cost carried in the control packet at each hop [35].

Local-based: The calculation is done in a greedy manner, which selects the best next-hop closer in distance to the destination by only using local information ([15], [20], and [13]). It is calculated on a hop-by-hop basis during data transmission.

Depending on the size of the network, Dijkstra and Bellman-Ford algorithm require costly CPU operations and considerable storage capabilities. Furthermore, the cost associated to the algorithms may change with the forwarding approach. Specifically, in a broadcast multi-rate forwarding approach, as there are various potential next-hop neighbor and rate choices, the number operations to carry out minimum path cost may increase [19]. On the other hand, as only local information is handled to compute the next-hop, local-based route computation tends to consume less considerable CPU.

The minimum path cost algorithm comes together with a routing metric. As mentioned in section II, the path cost is quantified by means of a routing metric, as opposed to the link cost, which is quantified by a link quality metric. The computation of a routing metric takes as input parameter a set of link costs calculated during the neighbor discovery process. A subset of these link costs will form part of the resulting minimum cost path. The cost represented by the routing metric in use may be calculated by means of three different methods. First, it may only use local information to compute the cost.

Second, it may be the sum of the weights of the cost of all links in the path.

(Recall that each link cost was previously calculated by the neighbor discovery building block.) Finally, additional information may be required to compute a more elaborated function.

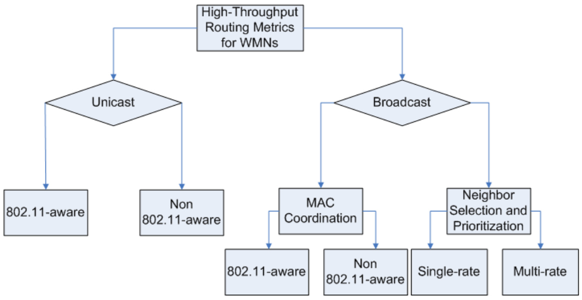

Figure 3. Taxonomy of Routing Metrics Issues

There are two different philosophies to compute the routing metric depending on the strategy followed in the forwarding approach component. They are categorized as unicast and broadcast routing metrics.

a) *Unicast Routing metrics*

Although any kind of antenna may potentially be used with protocols employing unicast routing metrics, these metrics are probably more suited for directional antennas.

One may group routing metrics into those not aware and those aware of the operation of the MAC protocol (see Figure 3). Focusing on 802.11 networks, some considerations follow for each of the groups.

Non 802.11-aware unicast routing metrics. In this case, the link metric does not directly take into account either link contention or channel usage or interference. Shortest path algorithms using as metric the sum of the weights of link metrics, like ETX [41] and ETT [1] are some representative proposals.

802.11-aware unicast routing metrics. Other metrics to calculate the optimal route are aware of the operation of the MAC layer. This routing metrics take into account the variation of wireless link quality in the route determination building block. Basically, the factors that are relevant to determine the quality of a path, and are captured by 802.11-aware routing metrics are the following ones:

Intraflow-interference: The interference due to packets belonging to the same flow. A common method to measure the intraflow-interference is to estimate how channel diverse are the links composing a path. As showed in table IV, intra-flow interference is captured in references ([1]-[3], and [38]).

Interflow-interference: This type of interference is usually calculated during link quality estimation by the neighbor discovery building block. References [3] and [38], as showed in table IV, capture inter-flow interference.

Literature on routing metrics often presents weighted average functions of different measured components ([1]-[3]), such as intra-flow or inter-flow interference. The link cost metric is modified by modeling some interference level which may be measured in different ways. A common feature in such approaches is that the calculated routing metric reflects the cost of the path from one single WMR to the intended destination.

On the other hand, [38] evaluates how the overall network performance would be degraded if a new WMR joins one of the different trees. Eventually, the WMR joins the tree that minimizes the global delay associated to transmitting a bit for all the WMRs in the forest, which is a union of trees rooted at the gateways, to its associated gateway. As a result, load balancing is explicitly provided. Therefore, the routing metric takes into account what would happen to the overall network quality when a new path is chosen.

TABLE IV.
MAC-Aware Unicast Routing metrics

Routing metric	Interference
WCETT[1]	Intra-flow
iAWARE[3]	Intra/inter-flow
MIC[2]	Intra-flow
MaLB[38]	Intra/inter-flow

b) *Broadcast Routing metrics*

This operation requires at least one static broadcast wireless interface per WMR. Additionally, WMRs are static and may be equipped with an omnidirectional antenna. Consequently, broadcast traffic distribution perfectly fits WMNs. In fact, broadcast routing metrics are usually associated to opportunistic routing protocols.

Though routing metrics belonging to unicast forwarding have been employed in broadcast forwarding [16], these routing metrics are not totally appropriate for these environments because they do not take into account all the potential path opportunities [22].

First, there is the issue of finding the optimal set of neighbors that guarantees maximum advancement to the intended destination, which is not present in unicast forwarding. This is similar in concept to the neighbor discovery building block. However, in this case, the discovery of the neighbors is dependent on the current intended destination.

Second, another singular issue is that of prioritizing neighbors amongst those in the selected neighbor set. The optimal candidate neighbor set is the union of neighbors in transmission range for a WMR that maximizes progress to the destination. Additionally, there exists a trade-off between the number of neighbors available (to maximize reception probability) and the number of neighbors that truly add some progress as next-hop. Thus, broadcast routing metrics are based on finding the optimal candidate neighbor set that adds more progress towards the destination. As shown in table V, one may classify the neighbor set selection and prioritization into two groups: single-rate and multi-rate (see also Figure 3).

Single-rate neighbor set selection and prioritization. Expected Any-path Transmissions (EAX) [21] and Remaining Path Cost (RPC) [22] metrics try to select and prioritize the number of forwarding candidates from all those belonging to the neighbor set of a WMR. As showed in table V, these proposals are based on generalizing the well-known ETX [41] metric to account for the expected number of anypath transmissions. The expected number of anypath transmissions is the estimated number of broadcast transmissions so that the intended destination could eventually receive a data packet.

TABLE V.
Broadcast Routing metrics

Routing metric	Rate	MAC coordination	Based on
EAX[21]	single	yes	ETX
RPC[22]	single	no	ETX
EAR[20]	multi	yes	Location info
EMT[24]	multi	no	ETT
EATT[19]	multi	no	ETT

In [22], all the possible neighbor WMR combinations at each potential next-hop in the path towards the intended destination are collected. After that, the optimal candidate forwarder is selected by using a generalization of Bellman-Ford algorithm.

Multi-rate neighbor set selection and prioritization. As showed in table V, location information has also been used to decide which WMRs of the potential neighbor set will forward the data packet [20]. And this selection is done by combining location information with an appropriate tuning of the underlying transmission rate, hence exploiting the underlying multi-rate transmission capabilities, to provide a heuristic for maximizing advancement to the destination at each hop.

In Expected Anypath Transmission Time (EATT) [19], wireless link quality is measured by checking the possible rates achievable. Furthermore, an algorithm to compute optimal routes based on Dijkstra is proposed. As for the metric, ETT [1] (see table V) metric is generalized to account for the multiple rates in an anypath environment. On the other hand, in [24], a generalization of the ETT metric is proposed as broadcast routing metric. The proposed candidate selection and prioritization may be computed using a distributed Bellman-Ford algorithm.

Finally, besides guaranteeing that an optimal neighbor set selection choice is made, the broadcast routing metric used must minimize the number of duplicated packets as well as packet contention. There are some common generic techniques to solve this issue. Some of them are based on introducing a scheduler algorithm aware of the wireless medium, while others exploit network coding, hence not needing additional coordination at all (Figure 3). As a result, the coordination strategy may be classified into two groups: 802.11-aware coordination and non-802.11-aware coordination (see table V).

802.11-aware coordination. References [16], [20], and [21] note that sending data packets in broadcast mode requires a scheduler to avoid duplicated transmissions by the potential forwarders. Thus, a coordination strategy to avoid (or minimize) this situation must be in place. In general, such a strategy is based on using timers associated to the MAC layer [20]. And it works as follows. Every data packet carries the WMR forwarding priorities calculated in the sending WMR. And these priorities are calculated by exploiting the available location information to determine the distance to the destination. Furthermore, the MAC broadcast layer is modified to transmit an ACK packet when a data packet is received. Then, a WMR candidate forwarder with j^{th} priority order may wait for the time needed for transmitting j-1 ACK packets before deciding to send if it does not overhead any previous ACK.

Furthermore, in [16] and [21], control messages are exchanged between the forwarding WMRs to schedule in order their forwarding attempts. Therefore, a WMR forwards a data packet only if higher priority WMRs failed to do so.

Non 802.11-aware coordination. With network coding, each receiver mixes received packets before forwarding them. Random network coding assures each receiver will not forward the same packets. Packets belonging to the same ([14], and [39]) or different ([34], and [35]) flows may be combined. The main advantage is that no explicit coordination between WMRs is needed because the probability that two WMRs use the same linear combination is quite low. Therefore, random network coding exploits spatial diversity and increases throughput due to the absence of such an explicit coordination scheme.

OPEN RESEARCH ISSUES

A list of the identified research topics related to the route determination building block that may need further work follows:

Interference estimation. A known problem faced by unicast routing metrics is how to quantify the two types of interference in the form of a routing metric. For instance, MIC [2] , iAWARE [3] and MaLB [38] capture intra-flow and inter-flow interference, but each proposal requires different methods for interference estimation. Therefore, there is no consensus in the research community in how to measure interference in a WMN.

Specifically, it is somewhat unclear whether information from lower layers (i.e., Physical and MAC) may be necessary to obtain accurate interference estimations. Therefore, a research direction may consist of measuring interference merely using the network level without resorting to lower layers. Furthermore, an evaluation of its achieved accuracy to see the necessity of using cross-layer interactions may be required.

Integration of the routing metric with the rest of components. The routing metric designed may not work properly with any routing computation algorithm. The design of the routing metric is tightly coupled with the design of the rest of the components of a routing protocol. For instance, it is shown in [2] that the WCETT [1] metric combined with the Dijkstra algorithm does not provide isotonicity, where isotonicity means that a routing metric should ensure that the weighted order of two paths is preserved if they are appended or prefixed by a common third path. Thus, WCETT cannot be calculated locally for each WMR and then simply perform a summation to obtain the cost of the whole path. In other words, WCETT requires a single calculation with the presence of all the WMR components involved in the path quality calculated by WCETT, namely the ETT of each link and the channel assigned to each link. Otherwise, the calculated routing path may be non-optimal or even may trigger routing loops. Therefore, the design of accurate isotonic routing metrics may be of interest.

Route recalculation timers. There is no consensus on appropriate values of the expiration timer that triggers the recalculation of the quality of a route. There is a trade-off between the optimal route choice and the stability of the route [23]. Frequent route path changes may lead to packets not received in order at the receiver. Thus, routing pathologies may occur at high scale. Some metrics may be needed to decide whether it is an advantage to change the routing path on a per-packet basis as anypath routing may assume.

Dijkstra and Bellman-Ford requirements. The overall overhead required for a minimum path calculation using algorithms such as Dijkstra or Bellman Ford is not scalable as network size increases. In fact, all WMRs must be aware of the link costs of the whole network. And this is not feasible in a large-scale WMN, even assuming that WMRs may embed powerful processors. Approaches to minimize or restrict such requirements to certain areas should be investigated.

Broadcast transmission limitations. The broadcast forwarding approach introduces one major issue, namely the absence of a reliability mechanism similar to that present in unicast forwarding. This may imply shifting reliability mechanisms to the routing level, i.e., guaranteeing reliability hop-by-hop, by areas, or in an end-to-end basis.

VI.TAXONOMY VS BUILDING BLOCKS

This section summarizes and qualitatively compares the most relevant features of each the routing protocols considered in this survey. Previous sections have highlighted the operation of their building blocks. In this section, we highlight and summarize the most relevant design decisions each routing protocol made for each of its building blocks (see table VI). Each representative routing proposal is tagged with a letter (A, B, C, D, E, F, G) identifying the classes defined in section IV. Furthermore, for each building block, we identify the more important aspects out of those discussed in section V.

As for neighbor discovery, we focus on the link quality metric as the more relevant aspect. As shown in table VI, the ETX [41] metric seems to be the most common approach employed in the literature. Some other relevant proposals choose the ETT metric [1], or even, not to estimate the link quality at all and merely use hellos to discover the neighbors. Another relevant link metric is iAWARE [3], which is used by MR-AODV [3].

As for control message propagation, table VI presents the propagation technique implemented by each routing proposal. Flooding is the most common approach followed by the generic routing approaches explored. But other relevant alternatives exist. For instance, an all-to-some approach is implemented in MCC [39], a tree-based approach in Hyancinth [11], and an efficient-flooding approach in DOLSR [31]. Another interesting observation is that in ROMER [15] and MGOR [24], control message propagation is not needed due to the specific operational characteristics of these protocols.

As for route determination, we take into account three main features. The first one is the interaction with the MAC layer when computing the routing metric (rightmost column in table VI). Furthermore, in case such interaction is present is based on two operational principles: 1) the MAC coordination (see the route determination building block), implemented by ExOR [16], MGOR [20], and DCAR [35], and 2) whether the routing metric takes into account the MAC layer, implemented by MR-LQSR [1], MR-AODV [3], and TIC [37]. The second feature examined for route determination, is the algorithm employed for minimum cost path computation, namely Dijkstra, Bellman-Ford, and local-based. As shown in table VI, the most common strategy followed by routing protocols shown is Dijkstra algorithm. This algorithm is used by MR-LQSR [1], MR-AODV [3], MORE [14], ExOR [16], SMAF [19], COPE [34] and TIC [37]. The Bellman-Ford algorithm is implemented by DSR [33], and DCAR [35]. And, the computation of the routes merely using local information is implemented by ROMER [15], and MGOR [20].

The third feature compared is the forwarding approach, chosen for transmitting data packets, namely unicast or broadcast. The unicast forwarding approach is used by MR-LQSR [1], MR-AODV [3], Hyacinth [11], TIC [37], DOLSR [31], and DSR [33]. On the other hand, broadcast forwarding is implemented by MORE [14], ROMER [15], ExOR [16], SMAF [19], MGOR [20], COPE [34], and DCAR [35].

TABLE VI.
Taxonomy vs Building Blocks Comparison.

C	Proposal	Neighbor discovery	Control message propagation	Route Determination		
				Forwarding approach	Route computation	MAC
A	MR-LQSR[1]	ETT	Flooding	Unicast	Dijkstra	Yes
A	MR-AODV[3]	iAWARE	Flooding	Unicast	Dijkstra	Yes
B	Hyacinth[11]	Hellos	Tree	Unicast	Local	No
B	TIC[37]	ETT	Flooding	Unicast	Dijkstra	Yes
C	DOLSR[31]	Hellos	Efficient Flooding	Unicast	Dijkstra	No
C	DSR[33]	ETX	Flooding	Unicast	Bellman	No
D	ExOR[16]	ETX	Flooding	Broadcast	Dijkstra	Yes
D	ROMER[15]	ETX	No	Broadcast	Local	No
E	MORE[14]	ETX	Flooding	Broadcast	Dijkstra	No
E	MCC[39]	ETT	All-to-some	Broadcast	Local	No
F	SMAF[19]	ETT	Flooding	Broadcast	Dijkstra	No
F	MGOR[20]	Hellos	No	Broadcast	Local	Yes
G	COPE[34]	ETX	Flooding	Broadcast	Dijkstra	No
G	DCAR[35]	ETX	Flooding	Broadcast	Bellman	Yes

As shown in table VI, there are not routing proposals that effectively and simultaneously take into account the most advances strategies found in the literature for all building blocks. For instance, for the neighbor discovery building block, there is some literature explicitly focused on improving the estimations of link quality. However, some of these relevant improvements ([4], [5]) are far from being integrated into a single routing protocol jointly with other recent improvements in other building blocks. In other words, existent proposals take into account one issue belonging to one specific building block, and they focus on improvements without deeply studying the potential implications in the other building blocks of the routing protocol.

OPEN RESEARCH ISSUES

A list of the identified generic routing open research issues that go beyond a single building block follows:

Routing in Cognitive WMNs (CWMNs). A CWMN is a WMN composed by mesh nodes equipped with cognitive radios. A cognitive radio is intended to sense the medium so that spectrum usage is maximized, hence incrementing the throughput transferred by the network. Such spectrum usage maximization implies learning the periods during which cognitive radios may use the available spectrum (i.e., the periods when users on licensed bands do not use the spectrum).

The introduction of cognitive radios adds several new open research issues to the routing procedures, especially when the availability of free spectrum bands is quite intermittent. Little research has been done in this direction, one recent proposal may be found in [42]. An open research issue is the synchronization between WMRs to common spectrum bands to perform opportunistic forwarding. Particularly, the potential solutions for this issue may have some similarities with approaches explored in the field of Delay Tolerant Networks (DTNs). However, in DTNs the forwarding opportunities are created based on node's physical movement and not spectrum band's dynamicity.

Honest WMR behavior. An open issue is how to guarantee honest behavior of WMRs. WMRs may behave selfishly, hence not contributing with their own resources to the routing of certain flows. This selfish behavior may lead to reduced throughput in the WMN. An incentive-based routing scheme that stimulates WMRs to route data packets belonging to other communication flows may be of interest.

Joint network coding and multi-rate transmission. Though the optimal multi-rate path was found in [19], network coding is not used to achieve maximum throughput. A proposal that combines network coding with multi-rate may outperform current multi-rate transmission and network coding approaches in terms of throughput when considered in isolation.

Joint network coding and multi-radio multi-channel WMN features. The combination of network coding and multi-radio multi-channel approaches may be explored. In fact, random network coding approaches found in the literature are designed for single-radio single-channel static WMNs. In a static non-power-constrained environment, there is not such a limitation. A proposal that effectively and jointly exploits multi-radio multi-channel operation and network coding may outperform current routing protocol results.

Network coding impact on routing. It is not clear the impact of network coding in the routing protocol. For instance, further work is needed to determine in what cases it is convenient to exploit coding opportunities, and also which flows should be combined.

Therefore, a research direction may consist of a evaluating the potential modifications to apply to a routing protocol augmented with network coding may do to maximize routing performance. Specifically, one immediate open question is whether it is necessary to add/update more building blocks to a routing protocol.

VII. CONCLUSIONS

To the best of our knowledge, this is the first survey focusing on routing protocols that really exploit the specific features of WMNs. These specific features may be summarized as the existence of a stable non-power-constrained backbone.

Therefore, and compared to other wireless networks, the main goal of such protocols may be shifted from connectivity to throughput maximization. In this paper, we provide a complete classification of routing protocols based on the way they exploit WMN-specific features (section IV). All current routing protocols for WMNs aiming at maximizing throughput may be mapped to one of the classes defined in the proposed taxonomy, which has two main branches. In the first one, we classify routing protocols that benefit from the addition of multiple radios configured in multiple channels to non-power-constrained WMN nodes. The second one includes routing protocols that benefit from the stability of the backbone along with the broadcast nature of the medium and, in some cases, the processing capabilities of the nodes.

Furthermore, we identify three common building blocks found in a high-throughput routing scheme for WMNs, namely neighbor discovery, control message propagation, and route determination (section V). Recent advances for each specific building block, as well as the design issues they may face in WMNs are also presented. Some insights on how to improve current routing approaches are also given. Specifically, for each building block, a detailed discussion of future open research issues to solve is provided. Finally, we mapped several relevant routing proposals present in the taxonomy to the most significant and common design choices chosen for each building block (section VI), thus linking the taxonomy and the building blocks explained in the previous section.

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José Núñez-Martínez was born in Barcelona, Spain, in 1979. He received the degree in Computer Science Engineering in 2004 from the Technical University of Catalonia (UPC). He worked as lab engineer in the Advanced Broadband Communications Center (CCABA) of Technical University of Catalonia (UPC) from 2003 to 2007. Since 2007, he is working in Center of Technological Telecommunications of Catalonia (CTTC) as a research engineer. His research interests include the design and implementation of routing protocols for wireless mesh networks, and wireless network performance measurements.

Josep Mangues-Bafalluy received the degree in Telecommunications Engineering in 1996, and the PhD degree in Telecommunications in 2003, both from the Technical University of Catalonia (UPC). Until 2003, he worked as a researcher in the Broadband Communications Research Group and the Advanced Broadband Communications Center (CCABA) of UPC, and as an assistant professor at UPC. Currently, he is a Senior Research Associate of the Center of Technological Telecommunications of Catalonia (CTTC) where he coordinates the activities of the IP Technologies Area of the Centre. He has participated in several Spanish (SABA1/2, SAM, ARTICO), EUREKA (Planets) and EC-funded (LONG), WIP, N++) projects. His research interest areas include mobility, self-organized networks and wireless network performance measurements.