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Improving B.A.T.M.A.N. Routing Stability and Performance

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Abstract

Wireless Mesh Networks (WMN) are diffusing quickly, especially to provide internet access to area difficult to reach using wired connections, a scenario which is typical of our region: Trentino in Italy. WMNs are also useful in situations of public emergency in order to quickly provide connectivity.

WMNs share all the problems widely studied in wired networks, such as congestion control, load balancing and fairness among users. Anyhow these issues in Wireless Mesh Networks are further complicated because of the nature of wireless communications that present a number of peculiarities such as significant packet losses, hidden and exposed terminals problems and stations mobility. These characteristics make solutions studied for wired networks work badly, or not working at all, in Wireless Mesh Networks.
As a consequence, all the aforementioned questions have to be studied from a new perspective. One may argue that all of this has already been studied, if not solved, in MANETs (Mobile Ad-hoc NETworks), however this is not true due to the different structure, more stable and hierarchical, of WMNs compared to MANETs.

One of the most notable problems is routing. It has been demonstrated that traditional hop count routing is sub-optimal in wireless networks, so a great number of specific routing protocols and metrics have been proposed. In this thesis, we have chosen to study B.A.T.M.A.N. as routing protocol, because it is one of the most diffused, and from many real experiments it results to have good performance. Furthermore it is sustained by an active community and has been also included in the Linux kernel.
This work is a continuation of a previous research project focused on B.A.T.M.A.N. overhead analysis and on a cross-layer metric improvement [1]. The know-how gained working on these topics was fundamental to achieve the necessary deep understanding of the protocol implementation.

In the introductory chapters we provide a general description of Wireless Mesh Networks from the routing perspective. We briefly list the most important families

of routing protocols, depicting advantages and drawbacks of each solution and reporting the current open research issues. We continue describing in detail the B.A.T.M.A.N. routing protocol, reporting its working principles and providing a list of the most important features.

After the introduction, we provide a formal analysis of the B.A.T.M.A.N. routing protocol metric, that till now was missing. Starting from the TQ metric properties, we verify consistency, optimality and loop-freeness of the routing protocol. We show that the current implementation presents some drawbacks that can lead to instability and also to the formation of routing loops. We then propose a modification of the protocol that solves these problems, also providing a formal proof of loop-freeness that is a crucial property of every routing protocol.

We conclude reporting the results of a number of tests executed using both virtual machines and real devices. Collected data confirm that current B.A.T.M.A.N. implementation converges slowly in case of node failures due to routing misbehaviours, and shows that the proposed modification actually solves these problems.

Contents

Chapter 1

Wireless Mesh Networks

A Wireless Mesh Network (WMN) is a communication network formed by nodes connected via wireless links. This family of networks differs from ad-hoc networks because, in the general case, not all nodes are peer one another, but a hierarchical topology is built based on a given set of node characteristics, e.g. power availability, dual radio, stability. WMNs differ also from Mobile Ad-hoc Networks (MANET) because nodes are typically characterized by reduced or absent mobility.

Wireless Mesh Networks have a lot of applications, for example they can be used for providing connectivity in emergency situations, or can be implemented to provide broadband connectivity to area difficult to reach using wired links, thus reducing digital divide. WMN are also used in military application to provide connectivity to units deployed in the battlefield.

Different aspects of WMN have been studied over last years. The main research areas are physical and MAC layer improvements, development of specialized routing protocols and application layer support.

In this chapter we give a description of WMN architecture, describing the current state of the art, focusing on routing protocols. For an exhaustive survey on WMN the interested reader can refer to [2].

1.1 WMN architecture

Wireless Mesh Network is a definition that includes a family of heterogeneous networks. Before moving to the routing part, it is necessary to understand how a WMN can be structured. In fact a routing protocol can be specifically implemented to exploit the characteristics of a given network architecture, or can

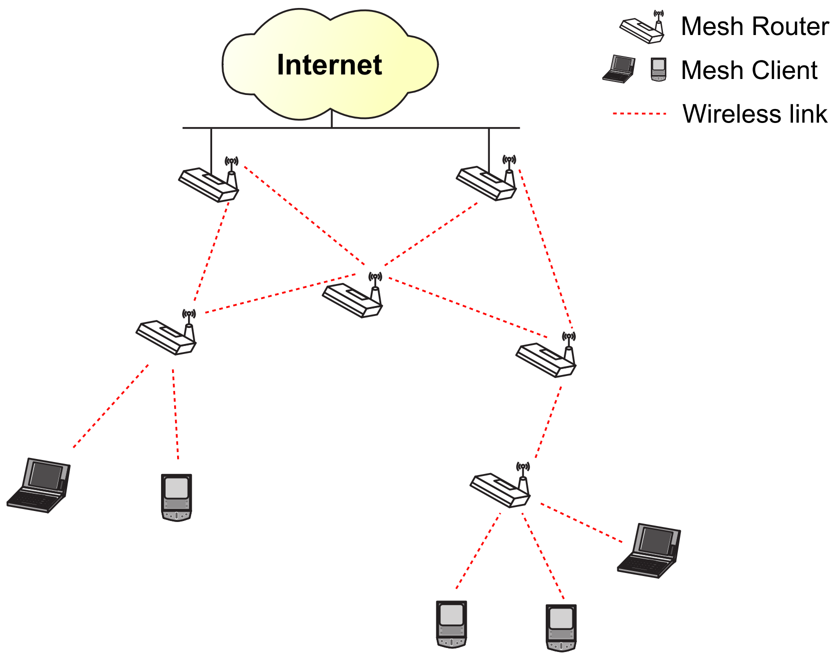


Figure 1.1: *A typical WMN topology presenting a mix of mesh routers, some of them acting also as gateways toward the Internet, and mesh clients that can be mesh aware or mesh agnostic.*

adaptively work in every different situation.

We start characterizing the nodes in the network dividing theme basing on their roles. Then we describe the most diffuse types of WMN.

1.1.1 Node characterization

A typical Wireless Mesh Network is depicted in figure 1.1. In a WMN, nodes can be divided in two categories: *mesh routers* (or mesh points) and *mesh clients* (or mesh stations). Mesh routers typically form the wireless backbone, and can act as gateways (*mesh gateways* or mesh portals) toward other networks, usually providing internet access to the mesh network.

Mesh clients can be further divided in two groups, *mesh aware* and *mesh agnostic*. The first ones participate directly to the routing protocol, the others are not aware of the existence of the WMN, and are connected to mesh routers as they were simple access points.

1.1.2 Network design

A WMN can be organized in multiple ways, depending on the purpose of the network. Basing on the functionality of the nodes, three macroscopic architectures can be described:

- **Infrastructure/Backbone WMN:** in this architecture, only mesh routers play an active role in the network. This configuration is very similar to a traditional 802.11 ESS, but in this case access points are connected through a wireless backbone instead of a wired one. Clients are completely unaware of the presence of the wireless mesh network.

- **Client WMN:** this architecture is a classic 802.11 ad-hoc network, with the presence of devices that cannot communicate directly, thus a multi-hop strategy is necessary. There is not any mesh router, all the clients participate actively to the routing protocol, so the routing is actually flat and not hierarchical.

- **Hybrid WMN:** it is the most general case. It is a combination of the infrastructure and the client architecture. An Hybrid WMN is composed of a fixed set of nodes forming the backbone, and a set of *WMN islands* connected to the backbone.

In the rest of the thesis, the reference architecture will be an hybrid one, because B.A.T.M.A.N. has been created to adaptively work in whatever type of network. Clearly this is an advantage, but can be also a drawback, because B.A.T.M.A.N. does not exploit the peculiarities of a particular family of WMNs to improve its performance.

1.2 Routing protocols for WMN

WMNs are particular case of Mobile ad-hoc networks (MANET) [3], and are also similar to Wireless Sensor Networks (WSN) [4]. The majority of routing algorithms proposed for MANET and WSN can work in a Wireless Mesh Network, but none of theme takes into account the particularities of such a network.
The most important characteristics of a WMN [5] are:

- **Mesh routers are relatively static and have no power constraint:** mesh routers tend to be fixed (e.g. on buildings).

- **Mesh clients can be mobile and power constrained:** mesh clients can be mobile and should not participate actively to the routing protocol, especially if they are battery-powered.

- **Mesh routers are frequently equipped with multiple radios:** in presence of multiple wireless interfaces, different strategies can be used to reduce interferences and/or increase bandwidth.

- **Traffic is concentrated along certain paths:** most of the traffic originates or terminates at the gateways.

- **Links present non uniform characteristics:** wireless links can presents variable bit-rate, packet loss ratio, etc. It is important to consider these parameters in routing decisions.

- **Network dimension:** potentially a WMN is designed to provide connectivity to a large community, so scalability and load balancing are important features.

It is important for a proper routing protocol to take into account these characteristics, possibly taking advantage from them.

1.2.1 WMN routing protocol families

In the last decade, many algorithms have been proposed specifically for WMN. They often derive from pre-existing routing algorithms created for MANET and WSN. Current routing protocols can be divided in three big families: reactive, proactive and hybrid. We intentionally do not considered static protocols, because they cannot adapt well to WMN where the network topology and the link conditions change constantly.

To give a finer taxonomy, according to [2], routing protocols can be classified basing on their performance optimization objectives. Another possible classification, proposed in [6], is based on existing differences in the procedures of route discovery and maintenance.

Actually it is hard to define a clear taxonomy, because in many case it is difficult to separate a routing protocol from its routing metric. Indeed in the cited surveys a routing metric is often reported together with the routing protocol description.

Reactive protocols

Reactive protocols build a path on demand, reducing the overhead traffic generated by the routing protocol. This increases scalability and helps reducing power consumption, allowing the protocol to be suitable also for power constrained devices. On the other hand the route establishment phase introduces a delay in the communication.

The most notable reactive protocols are AODV [7] and DSR [8], which are both based on flooding for route discovery on demand. The main difference between the two protocol is that AODV implements hop-by-hop routing while DSR uses source routing.

Proactive protocols

In contrast to reactive ones, proactive routing protocols, such as OLSR [9], maintain current paths towards all the destinations removing any routing establishment delay. Routing information are propagated in the network using flooding, thus presenting a greater overhead compared to reactive protocols. Scalability issues can be attenuated using particular flooding techniques. Proactive protocols cannot be used with power constrained devices, because they need continuous transmission that would rapidly drain the battery.

Hybrid protocols

Another family of routing protocols is called hybrid, and try to mix reactive and proactive techniques to exploit their advantages and prevent from their drawbacks. An example of hybrid protocol is HWMP that is the default and required routing protocol in the IEEE 802.11s [10] definition. It is based on AODV to establish connections between Mesh Stations, while Mesh Portals maintain up-to-date routes toward all nodes in a proactive way.

1.2.2 Types of routing protocols

A routing protocol is formed of a path calculation algorithm, that works using a specific routing metric, and by a packet forwarding scheme, necessary to propagate routing information in the network. We briefly describe the most common path calculation algorithms and forwarding schemes used in wireless mesh networks, listing the main advantages and disadvantages.

After this classification, we can derive for a given protocol, knowing its path calculation algorithm and its forwarding schema, the necessary formal properties that a routing metric, used in combination with the protocol, must respect to guarantee features like loop-freeness, consistency or optimality.

Path calculation algorithms

Path computation algorithms are used to compute the best path toward every destination according to a certain routing metric. Proactive routing protocols for WMN, similarly to routing protocols used in wired networks, use the Bellman-Ford algorithm (distance vector) or the Dijkstra's algorithm (link state). These protocols need a constant update of routing information, obtained via periodic exchange of routing information. This mechanism introduces an overhead that can become a problem, especially in large ad dense networks. To overcome these problems, different strategies has been proposed, they consist on reducing the frequency of updates and/or aggregate them. In OLSR, for example, routing information are propagated in the network using an optimized flooding technique based on multipoint relays (MPR) [9] that form a hierarchical logical topology thus permitting to aggregate routing information.

Reactive routing protocols, on the other hand, use source initiated flooding to find a suitable route toward a required destination. The overhead in this case is reduced, because routing frames are sent only when it is needed. The flooding procedure can also be optimized to further reduce the overhead and speed up the route discovery process. A similar improvement has been proposed in AODV-ST, where has been implemented a spanning tree protocol to reduce overhead [11].

Packet forwarding schemes

Two packet forwarding schemes exist, source routing and hop-by-hop routing.

In source routing the entire path (or a unique route sequence number) is written in each packet header, so every node, upon receiving a packet, essentially reads the header and forwards the packet accordingly. This scheme is very robust since it can be easily used to ensure consistency and loop-freeness. The main drawback is the additional overhead, that anyhow can be reduced using path sequence numbers as in AODV.

In hop-by-hop routing instead, every node maintains a list of next-hops toward each destination. Packets are forwarded to the current best next-hop until they reach the final destination. This scheme has much lower overhead, but it is more prone to problems such as loop formation and slow convergence (counting to infinity problem). Proper solutions to avoid these problems need to be implemented, especially in case of rapidly changing network conditions, a typical scenario of networks with mobile devices.

1.3 Routing metrics for WMN

A number of metrics have been proposed in the literature, depending on network characteristics and purposes. For example some routing metrics maximize the stability of a path considering loss probability, some focus on optimizing throughput measuring link bandwidth, while others are concerned on energy consumption.

All proposed metrics have both advantages and drawbacks, and adapt well to specific situations. In any case none of them captures all the important qualities of a path, and we are still far from the definition of a general metric. This is probably due to the great number of possible typologies of WMN that in many cases have specific requirements.

In this section we briefly list the most notable routing metrics for WMN, dividing them basing on the degree of knowledge of the link characteristics. For a comprehensive list of routing metrics and their characteristics see [6].

1.3.1 Quality unaware metric

The simplest metric that can be used in WMN is the hop count. This simple metric perform decently in network with high mobility since it rapidly finds available routes. In more stationary networks, typical of WMN backbones, instead it performs quite bad since it is not able to capture the quality differences between available paths.

As a consequence, all the links are considered as equal so the path with the minimum length is chosen. We know that in wireless networks the actual rate depends on node distance, so it is easy to imagine that choosing long and slow links, can lead to sub-optimal routing configurations and poor performance.

1.3.2 Quality aware metrics

Quality aware metrics consider the peculiarities of wireless links such as loss probability, bit-rate and inter and intra-flow interference. Complex metrics often need a cross layer implementation to access physical layer information. This approach has been shown to be quite promising for the definition of better WMN routing metrics [2]. In fact the physical layer is aware of characteristics of wireless links otherwise difficult to measure at higher layers, such as channel frequency, physical bit-rate and signal strength.

This approach helps also in presence of mixed wired and wireless links, or in presence of different types of wireless links (802.11bgn), permitting to distinguish between interface types thus favouring links with higher capacity and stability.

In this section we briefly list the most common properties of a wireless link, indicating some of the most diffuse routing metrics proposed in the literature taking into account these properties.

Link reliability

A first evaluation of link quality can be done measuring link reliability in order to identify more stable routes. An example is the ML [12] metric which estimates path loss rate multiplying local link loss probabilities. ETX [13] instead tries to estimate the expected transmission count, that depends on link reliability since transmission count increases in case of physical layer retransmission caused by losses.

Link rate

Those metrics focusing on optimizing the bandwidth have to take into account the transmission speed of links, that can be time variable. A popular bandwidth metric is ETT [14] that estimates the expected transmission time of each link considering also the packet size. ETT is obtained multiplying ETX by the average packet delivery time. Another notable example is MRS [15], it uses paths having maximum bit-rate while minimizing transmission power to reduce interferences. MRS partial experimental results[1] are reported in [16] showing an interesting improvement of measured throughput with respect to ETT.

Interference

Interferences have an huge impact on wireless performance, they can be divided in intra-flow and inter-flow. Interference is not a local link properties but instead is influenced by a number of factors that regard the entire path, the network topology and the traffic load.

Intra-flow interferences are those concerning a single data flow traversing multiple links sharing the same wireless channel or links using partially overlapping channels. In this situation we know that each node in the same collision domain cannot transmit and receive at the same time, and only a node at a time can transmit. Metrics that consider intra-flow interference are able to favour paths

[1]Experiment was realizing only with the bit-rate part due to problem dealing with power control on real devices.

with the minimum channel share thus increasing the network capacity. An example metric is WCETT [14] that combines links ETT in a particular way that penalizes links sharing the same collision domain.

Inter-flow interference instead is related to concurrent flows sharing the same wireless resource, and is more difficult to measure as it varies due to network load. The metric iAWARE [17] attempts to measure interference monitoring signal to noise ratio (SNR) and signal to interference and noise ratio (SINR) toward neighbours. Another approach, employed in the MIC [18] metric, is to count the number of interfering nodes to get an estimation of the inter-flow interference degree.

Load

An aspect difficult to consider in wireless networks, and also in wired networks, is link load and load balancing. Implementing routing metrics that consider load can lead to instability situations and frequent route changes (a phenomena also known as *route flapping*).

A notable attempt to consider load in WMN routing is the BLC [19] metric, which is defined as the minimum residual capacity on a path considering also its length. Another metric considering link load is the PktPair [20], it measure, using the packet pair technique, the delay caused by node queuing and channel occupation, obtaining an estimation of the load along a path.

Chapter 2

B.A.T.M.A.N.

B.A.T.M.A.N. [21] (Better Approach To Mobile Ad-hoc Networking) is a promising and quite diffuse routing protocol for Wireless Mesh Networks. From real world experiments it results to have good performance compared to other WMN routing protocols [22]. It has been also included in the Linux kernel from version 2.6.38, and this fact is a confirmation of the maturity of this project.

B.A.T.M.A.N. belongs to the proactive routing protocols family, and it can be categorized as a distance-vector routing protocol with an hop-by-hop forwarding scheme. It is based on a destination initiated periodic flooding of routing management frames called OGMs (Originator Messages). These packets announce the presence of the station and are used to discover and maintain routes.

B.A.T.M.A.N. working principle is somehow similar to DSDV [23]. Routing management frames are marked with unique sequence numbers, both to check the age of routing information and prevent from the formation of routing loops. The main difference is that in B.A.T.M.A.N. sequence numbers are independently applied to each routing table entry, while in DSDV a sequence number identify the entire routing table. B.A.T.M.A.N. differentiates from DSDV also in route advertisement frequency, because OGM are sent periodically and not in response to routing table or topology changes. This is necessary because OGMs are used also as sample frames to measure the link quality used to calculate the routing metric.
As a result, every node knows all the other nodes in the network and maintains a list of available next-hops toward them. The best next-hop, called router, is chosen accordingly to a path quality metric called TQ (Transmission Quality) that will be formally described in the next chapter. B.A.T.M.A.N. can also be used in generic mesh networks with heterogeneous interface typologies, anyhow

the performance of the protocol in this case can be poor because the TQ routing metric does not distinguish between wired and wireless links nor between fast and slow links.

2.1 The B.A.T.M.A.N. dictionary

We will use a number of terms specific of the B.A.T.M.A.N. world that are actually used in the available documentation and also in the source code. In many cases these terms differ from the ones used in the previous chapter, so before proceeding in the protocol description, it is necessary to briefly list the specific terms used to describe the network entities.

- **Originator:** a node in the network participating actively to the routing protocol. It has a unique address (level 2) in the network and can have multiple physical interfaces.
- **Neighbour:** an originator which is reachable directly (one hop) through whatever physical interface.
- **Router:** a candidate neighbour to be next hop toward a specific originator. The routing protocol identify the best router for each originator according to a specific metric called TQ.
- **Client:** a mesh unaware node connected to an originator acting as an access point or mesh portal.
- **Gateway:** an originator acting as a gateway toward another network (i.e. the Internet).

2.2 Originator Messages

The overview of the B.A.T.M.A.N. protocol necessarily starts from the description of Originator Messages (OGM). They are the core of the protocol, since these packets are used for neighbour discovery, route information flooding, and lastly but not least for estimating the quality of links and paths they traverse.

The structure of an OGM is illustrated in figure 2.1. It contains the unique MAC address of the source station (called *Originator*), the address of the previous sender and the Transmission Quality (TQ) of the path it has traversed (set to the

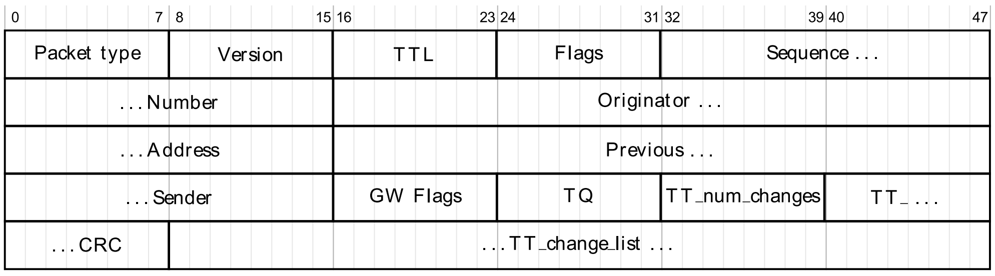


Figure 2.1: *OGM packet structure*

maximum value of 255 when the flooding starts). In addition it contains a TTL field necessary to ensure flooding termination, and a sequence number (SN).

In order to give a more clear description of the protocol, we will logically divide OGMs in Local and Path OGMs. Local ones are used to compute link quality, while path OGMs are used to propagate routing informations through the network.

2.2.1 OGM flooding

OGM flooding is initiated periodically by each originator, that every ORIG_-INTERVAL broadcasts its Originator Message. The packet contains the station address in the Originator Address field. The TQ value is set to TQ_MAX_VALUE that in the current implementation is 255, while the Previous Sender field is left empty.
Upon the reception of a new OGM (one containing a never seen sequence number), each station rebroadcast the OGM putting in the TQ field its best TQ toward the originator. In this way routing information are propagated in the network.

2.2.2 Data structure

The entire protocol depends on the maintenance, in each node, of a set of data structures that are different for neighbours and originators. For a complete understating of the mechanisms at the basis of B.A.T.M.A.N. it is necessary to describe accurately these structures.

Originator data

For each originator O, it is maintained the sequence number SN_O of the latest OGM packet received and a list of available router candidates. A router candidate is defined as a node from where at least an OGM of O has been received. For

each candidate router $R_i(O)$, it is maintained a sliding window containing the TQ read in the OGM coming from O and received via R_i. The dimension of the sliding window is fixed to TQ_GLOBAL_WINDOW_SIZE [1].
The quality of a path is obtained calculating a particular average of the received TQ values contained in the global window. If a number of OGM equal to TQ_-GLOBAL_WINDOW_SIZE is not received via a particular candidate router R_i, its TQ becomes 0 so it is no longer considered as a valid next-hop.

Neighbour data

For each neighbour, are maintained two sliding window of fixed dimension TQ_-LOCAL_WINDOW_SIZE [2]. The first one is used to count the OGM correctly received from the neighbour, while the second one is necessary to count own OGM echo received from the neighbour. These local windows are used to estimate the quality of links toward neighbours. Local link TQs are then combined to obtain the path quality.

2.2.3 Local OGM

Local OGMs are those used to estimate the quality of a link in term of loss-probability. They can be divided in:

- **Neighbour OGM:** OGM of direct neighbour (1-hop neighbours). Previous sender field is empty.
- **Echo OGM:** own OGM rebroadcast received from a neighbour. In this case the previous sender field is equal to receiving station address.

Depending on the type of received OGM, the station behaves differently.

Neighbour OGM

When a station receive an OGM from a neighbour, it does the following operations:

1. If the station is not known, create a new neighbour entry.
2. If the sequence number is greater that the maximum SN registered for this neighbour, shift the sliding window accordingly.

[1]The value of TQ_GLOBAL_WINDOW_SIZE is 5 in the current release.
[2]The value of TQ_LOCAL_WINDOW_SIZE is 64 in the current implementation.

3. Register on the neighbour window the reception of the OGM with the Sequence Number contained in the packet.

4. Rebroadcast the OGM updating TQ (see section 2.2.5 for details), reducing TTL, and replacing previous sender.

Echo OGM

Upon receiving a so called OGM echo, a station perform the following operation:

- Register on the neighbour echo window the reception of the OGM echo with the Sequence Number contained in SN field.

- Discard the packet.

2.2.4 Local Link Quality

Quality of a local link is estimated indirectly using OGMs received from the neighbour station. Thanks to sequence numbers, the received OGMs can be "counted" using a sliding window of fixed dimension TQ_LOCAL_WINDOW_-SIZE. Receive quality (RQ) is defined as the fraction of OGM received in the current sliding window.

Clearly it is not sufficient to count the originator messages received, because we need to estimate the transmission quality (TQ), not the receive quality (RQ)[3]. To solve this problem, each node registers, in another similar window, also re-broadcast of its own OGMs received from the neighbour. In this way a so called *Echo Quality* (EQ) is obtained.

Transmission quality of a link from node A to node B can be derived from RQ and EQ observing that:

$$EQ_{AB} = TQ_{AB} \times RQ_{AB}$$

from which it is easy to obtain transmission quality:

$$TQ_{AB} = \frac{EQ_{AB}}{RQ_{AB}}$$

The mechanism is schematized in figure 2.2

[3]In wireless networks, typically links are not symmetric and present different characteristic in the two directions.

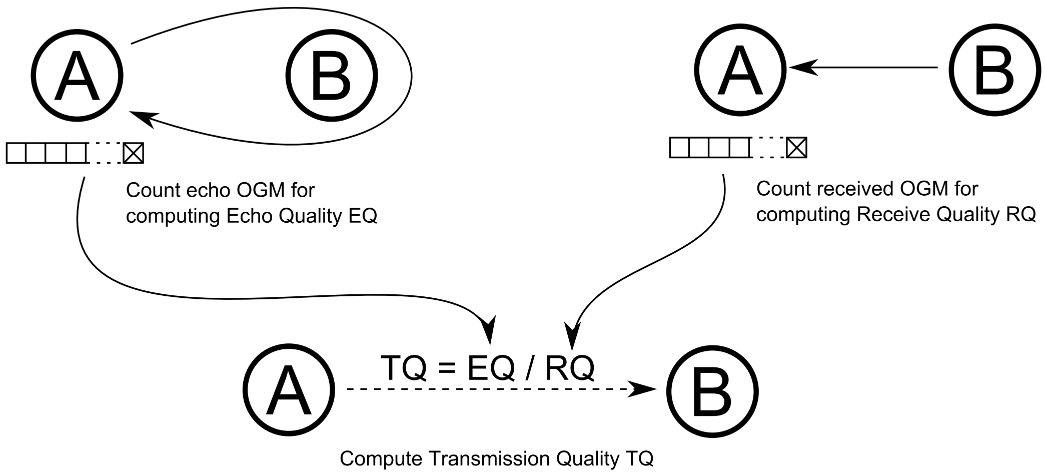

A
B
A
B
Count echo OGM for computing Echo Quality EQ
Count received OGM for computing Receive Quality RQ
TQ = EQ / RQ
A
B
Compute Transmission Quality TQ

Figure 2.2: *The mechanism used by B.A.T.M.A.N. to estimate link transmission quality counting received OGMs and echoed OGMs.*

Asymmetric links penalization

Considering only transmission loss probability of a wireless link is not sufficient. In fact if a link has a poor receive quality, physical acknowledgements are likely to be lost, causing retransmissions that produces a performance degradation. So TQ of asymmetric links is reduced multiplying it by an inverse cubic function of the RQ:

$$TQ_{AB} = TQ_{AB} * (1 - (1 - RQ_{AB})^3)$$

This formula does not derive from particular measurements or study, it is only an heuristic that penalize those link having low RQ values.

2.2.5 Path OGM

Path OGMs are used to flood routing information through the network, they are propagated using well defined forwarding rules. As already mentioned, for each originator o, it is maintained the sequence number SN_o of the latest OGM packet received, the list of available next-hop neighbour with their TQ windows, and the current best neighbour r (also called router). Each station, upon receiving an OGM m from neighbour n with a TQ value TQ_m and a sequence number SN_m behaves as follow:

1. If $SN_m > SN_o$:

    - update SN_o to new value SN_m and move the sliding windows of each available next-hop neighbour accordingly

- insert in the latest position of n sliding window the value TQ_m
- insert in the latest position of the other candidate neighbour window the value 0
- recompute the average TQ for all candidate neighbours
- if m results to have the best average TQ, set it as current router r
- decrease the TTL of m
- if $n = r$ set $TQ_m = TQ_m * \text{HOP\_PENALTY}$, else set TQ_m to average TQ of router r.
- rebroadcast the OGM m

2. If $SN_m = SN_o$:

   - put in the latest position of sliding window of neighbour n the value TQ_m
   - recompute the average TQ for all candidate neighbours
   - if m results to have the best average TQ, set it as current router r
   - discard the packet.

3. If $SN_m < SN_o$:

   - discard the packet as old.

Packets are also discarder if the TTL field reaches 0, preventing flooding to continue forever in case of routing problems.

Shortest hop count route

Before the OGM rebroadcast it is applied a penalty to the TQ. This reduction is necessary to penalize longer path in case of similar TQs. The formula used in the current implementation is:

$$TQ = TQ * \frac{(\text{TQ\_MAX\_VALUE} - \text{TQ\_HOP\_PENALTY})}{\text{TQ\_MAX\_VALUE}}$$

where TQ_HOP_PENALTY has a default value of 10, while TQ_MAX_VALUE is fixed to 255.

OGM fast forward

From the implementation described above it emerges a mechanism that can be called *OGM fast forward*. It can be observed that the first fresh OGM coming from whatever neighbour is immediately forwarded with a TQ equal to the current router TQ average.

This is a subtle observation but has a great impact on routing metric properties causing protocol misbehaviour, as we will see in the next chapter.

2.3 A layer 2 protocol

Most of the current mesh routing protocol implementation works at layer 3 (e.g. olsrd and babel), but some implementations have started moving on layer 2. The most notable example is open802.11s which is a partial implementation of the IEEE 802.11s standard.

B.A.T.M.A.N. after a first implementation on layer 3 (batmand), has been ported to layer 2, or better, between layer 2 and 3. This choice has both advantages and disadvantages. We will briefly describe the most important peculiarities of such an implementation.

2.3.1 Advantages

Transparency

All nodes in the mesh network are seen as attached to a unique Ethernet broadcast domain. Consequently layer two protocols are completely unaware of the existence of the mesh network, and even more important, the network communication does not depend on IP. Therefore B.A.T.M.A.N. can be used with whatever layer 3 protocol.

Multiple interfaces

A station owning multiple interfaces, possibly of different type[4], can let all them participating to the mesh. The result is the possibility of connecting physically different network segments obtaining a virtually unitary broadcast domain.

Multiple interfaces can be used also to increase the throughput. If multiple connections exist toward a node, they can be used contemporaneously in a round

[4]The only requirement is the capability of sending Ethernet frames.

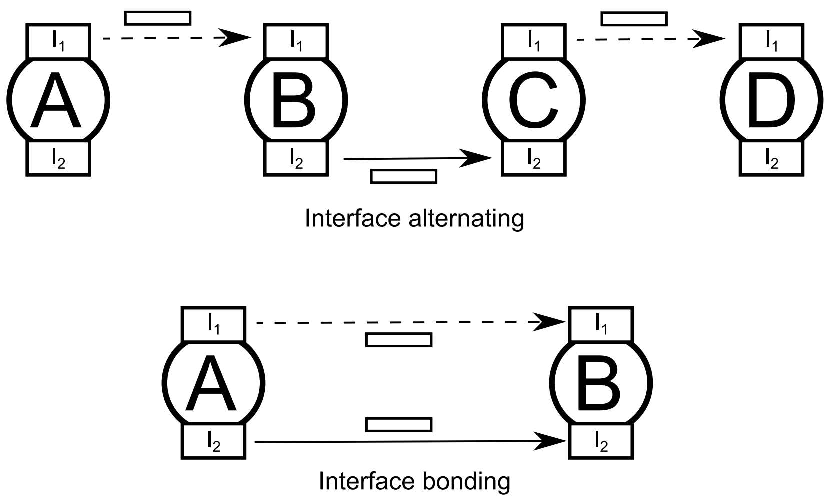


Figure 2.3: *Alternating and bonding strategies to exploit the presence of multiple independent interfaces. Alternating allows simultaneous reception and send along a path. Bonding exploit multiple independent wireless link to increase local link throughput.*

robin fashion (Interface bonding) in order to distribute the load among all the links. The drawback of this mechanism is that the throughput is limited by the worse link in term of capacity and losses.

Another possibility is to use multiple links along a path alternatively to send and receive packets (Interface alternating). In this way can be reduced the intra-flow interference, allowing a node to transmit and receive simultaneously[5].

By default in B.A.T.M.A.N. enables only the interface alternating solution, while bonding is disabled. Both the mechanism are illustrated in figure 2.3.

2.3.2 Disadvantages

Addressing

MAC addresses used by the routing protocol are substantially "flat", in contrast to IP addresses that are structured and carry information about the structure of the network. This can be seen as a marginal oddity, but instead introduces serious scalability problems since routing tables cannot be organized and compressed.

This problem rises up also for client [6] management since MAC addresses have to be used. If client number increases, the overhead becomes significant, since their addresses are appended to Originator Messages. A proper mechanism to

[5]In case of multiple wireless interfaces, the radio channels have not to be overlapping.
[6]For client we intend a mesh unaware station connected to a mesh router acting as access point.

reduce the overhead caused by client announcement has been developed in [24].

Fragmentation

Along a path can be encountered interfaces presenting different MTU, thus a proper fragmentation mechanism has to be implemented from scratch since IP fragmentation cannot be used. For this reason it is strongly recommended to set MTU of interfaces participating to the mesh protocol to 27 bytes more than the B.A.T.M.A.N. interface MTU. This allows B.A.T.M.A.N. header (27 bytes) to be contained in a single Ethernet frame.

2.3.3 Other feature

Since the initial implementation, a number of corrections and improvements have been introduced. In this section it is reported a description of the most notable ones. This list does not pretend to be completely exhaustive, for a better understanding of all the characteristics of B.A.T.M.A.N. the reader can refer to the source code [7] and to the website of the project [8] .

OGM aggregation

OGM aggregation has been implemented to reduce the overhead caused by sending many small OGM packet. Each time an Originator Message has to be sent, an aggregated packet is created and following OGM to broadcast are enqueued up to a maximum aggregation size (MAX_AGGREGATION_BYTES). A time limit for aggregation is also introduced, so an OGM can be delayed up to maximum aggregation time (MAX_AGGREGATION_MS).

Multiple send of broadcast packets

Broadcast packets do not receive physical acknowledgements, so the probability of delivery is directly related to the loss-rate of the links. In a multi-hop wireless mesh network the loss rate becomes significant as the path length increases. In order to increase probability of success, each packet with broadcast destination address is sent multiple time. In the current implementation each packet is sent twice. It is a matter of the recipients to verify and discard duplicated packet.

[7]The git repository can be find at http://git.open-mesh.org

[8]http://www.open-mesh.org

Gateway mode

A frequent scenario of use of WMN is the Internet access, thus involving *mesh gateway*. A B.A.T.M.A.N. node can be configured to advertise itself as gateway, indicating also its available bandwidth. This is done using apposite fields of the Originator Message.
Upon receiving multiple gateway advertisements, each station chose a default gateway based on the current TQ toward the various candidates.
This feature is also useful to directly forward DHCP request in unicast to the gateway, avoiding to send them in broadcast, so reducing the overhead and the loss probability.

Fast roaming

In case of mesh clients moving from a mesh access point to another, a solution to speed up the roaming delay has been implemented [24]. In fact the mechanism of announcing clients in OGMs introduces a period, in the order of seconds, in which packets directed to the client are discarded.

The fast roaming is based on *Roaming Advertisement*, that are sent in unicast from the new access point to the old one when a roaming is detected. In this way, while the basic client announcing via OGM converges to the new configuration, the old access point can temporally forward client packets to the new access point. This mechanism causes a transitional increase in the network latency, since a sub-optimal path is used, but guarantees nearly uninterrupted connectivity.

Chapter 3

B.A.T.M.A.N. is neither optimal nor loop-free

The notable characteristic that distinguish B.A.T.M.A.N. from other routing protocols, is that routing management frames are used both to disseminate routing information and to directly measure the quality of links. In particular OGMs are sent in broadcast to test link reliability, so there isn't any guarantee of delivery of routing management packets. It is not clear whether these losses modify routing protocol properties such as optimality, consistency and loop-freeness.

We want to provide a formal definition of the TQ metric in term of loss probability of links. Then the formal work done on general routing protocol about properties such optimality, consistency and loop-freeness is revised for B.A.T.M.A.N. analysing how these properties change in presence of OGM losses.

We will see that the current implementation presents important implementation and conceptual errors, that can lead to the formation of routing loops. We then propose a modification of the current implementation in order to guarantee loop freeness.

3.1 TQ and loss probability

The formal analysis of the B.A.T.M.A.N. protocol is fairly complex because OGMs, as we have seen, are used both to measure link quality and to propagate routing information. The logical division between local link TQ measurement and path TQ calculation introduced in chapter 2 is maintained in this formal definition, allowing to split the analysis of the protocol in two independent parts.

We start describing local TQ calculation, measured using link OGMs, and

SYMBOL	MEANING
$a, b, c, \cdots$	nodes in the network
$\mathcal{P}, \mathcal{Q}, \cdots$	paths in the network
$R(a, b)$	Best path from node a to node b calculated using the route calculation algorithm R
$\overrightarrow{S}(a, \mathcal{P})$	Successor node (router) of node a in the path $\mathcal{P}$
$TQ(a, b)$	Local TQ from node a to node b (a and b are neighbours)
$\overline{TQ}_a(\mathcal{P})$	TQ average toward a via $\mathcal{P}$
$TQ_a^k(\mathcal{P})$	TQ toward node a via $\mathcal{P}$ contained in OGM with sequence number k

Table 3.1: *Table of symbols used in the chapter.*

its relation with the physical property of the link that the TQ metric tries to estimate. Then we will describe how link TQs are combined to estimate the path TQ, describing also the real implementation based on path OGM.

We will use the notation $p_T(o_1, o_2)$ and $p_R(o_1, o_2)$ to indicate respectively the successful probability of transmission and reception of a packet on the link between originators o_1 and o_2. Similarly $p_E(o_1, o_2) = p_T(o_1, o_2)p_R(o_1, o_2)$ denotes the request-response (echo) probability of success.

The notation used in this chapter to give a formalization of the TQ metric and of the routing information propagation is summarized in table 3.1.

3.1.1 Local TQ

Local Transmission Quality of a link from originator o_1 to o_2, indicated with $TQ(o_1, o_2)$, measure the probability of successful transmission. It is defined as:

$$TQ(o_1, o_2) = p_T(o_1, o_2)(1 - (1 - p_R(o_1, o_2))^3) \tag{3.1}$$

where $(1 - (1 - p_R(o_1, o_2))^3)$ is a coefficient that biases the metric against asymmetric links. This particular cubic function of p_R, according to the programmers, is intended to slightly penalize those links having a p_R near 1, while it heavily penalizes links with p_R near 0.

We have seen in chapter 2 that probability of successful transmission p_T is estimated dividing the percentage of received OGM echoes by the percentage of OGM received from the neighbour. It is important to notice that local OGM losses do not influence the properties of the routing metric, because local OGMs are only used to measure the quality of a link. In reality the loss of a link OGM can corresponds to a path OGM loss because in the implementation there isn't any difference between the two message type. Anyhow we still maintain the aforementioned logical division and treat losses separately.

3.1.2 Path TQ

The Transmission Quality of a path derives from the multiplication of local TQs of the links composing it. It expresses the probability of successful transmission through a path, that is the product of success probabilities of each link. Each local TQ is also weighted by a coefficient, called HOP_PENALTY, having value $(1 - \alpha)$ with $0 < \alpha < 1$. The objective of this coefficient is to penalize a longer path in case of equal successful probability.

As a result, the quality of the path $\mathcal{P}$ having length $n > 1$ and traversing nodes $\langle o_1, \cdots, o_n \rangle$, can be expressed as:

$$TQ(\mathcal{P}) = (1 - \alpha)^{n-1} \times \prod_{i=1}^{n-1} TQ(o_i, o_{i+1}) \tag{3.2}$$

The calculation of these values in B.A.T.M.A.N. is done using periodic OGM flooding initiated by each node. As the OGM traverses the network, each node inserts in the TQ field the actual TQ toward the originator and propagate the information to the other nodes according to the forwarding rules examined in section 2.2.5.

3.2 Routing protocol properties

A routing protocol, to ensure proper operations, must satisfy three major properties: consistency, optimality and loop-freeness. In [25] Yang and Wang defines the necessary requirements for the routing metrics, in order to guarantee these properties for different routing protocol families. The results are summarized in table 3.1.

B.A.T.M.A.N. can be treated as distance-vector despite it is based on periodic source initiated flooding of OGMs to propagate routing table updates. This particularity does not modify the protocol classification, as in any case the routing algorithm used is the Bellman Ford one.

Routing protocols	Optimality	Consistency	Loop-freeness
Flooding-based route discovery + source routing	right-isotonicity		
Flooding-based route discovery + hop-by-hop routing	right-isotonicity + strictly left-isotonicity	right-isotonicity + strictly left-isotonicity	circle detection mechanism
Dijkstra's algorithm + source routing	right-isotonicity + right-monotonicity		
Dijkstra's algorithm + hop-by-hop routing	right-isotonicity + right-monotonicity + strictly left-isotonicity	right-isotonicity + right-monotonicity + strictly left-isotonicity	right-isotonicity + right-monotonicity + strictly left-isotonicity
Distributed Bellman-Ford algorithm + source routing	left-isotonicity		
Distributed Bellman-Ford algorithm + hop-by-hop routing	left-isotonicity + left-monotonicity	left-monotonicity	left-monotonicity

Figure 3.1: *Routing metrics requirement for different types of routing protocol necessary to obtain consistency, optimality and loop-freeness. The table is taken from [25].*

We start reporting the formal definition of routing metric and the definition of monotonicity and isotonicity of routing metric as defined in [25], opportunely adapted to the TQ metric that is monotonically decreasing. Also the definition of routing protocol consistency and optimality are reported.

Then we formally define the TQ metric in order to verify the aforementioned properties for the TQ metric. We provide two different demonstrations both for an ideal loss free case and for a real situation with OGM losses, evidencing some problem of the routing protocol in case of losses and proposing a possible solution.

3.2.1 Routing metric and its properties

A routing metric can be defined as an algebra on top of a quadruplet $(S, \otimes, w, \succeq)$, where S is the set of all paths, w is a function that maps a path to a weight, $\succeq$ is an order relation, and $\otimes$ is the path concatenation function.

The function w capture the quality of a path according to certain parameter such as length, delay, bandwidth and others. We say that a path a is better than (or equivalent to) a path b if $w(a) \succeq w(b)$.

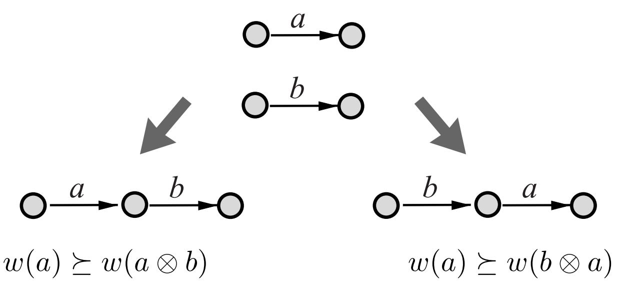
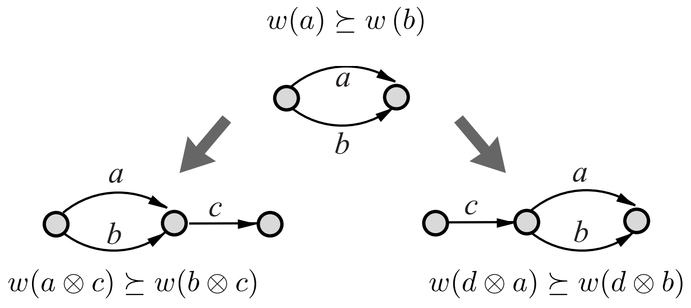


Figure 3.2: *Graphical representation of right and left monotonicity.*

Monotonicity The algebra on top of $(S, \otimes, w, \succeq)$ is defined as monotonic if $w(a) \succeq w(a \otimes b)$ (right monotonicity) and $w(a) \succeq w(b \otimes a)$ (left monotonicity). If the $\succeq$ is strictly $\succ$ we say that the metric is strictly monotonic.



$w(a) \succeq w\,(b)$
a
b
a
b
c
c
a
b
$w(a \otimes c) \succeq w(b \otimes c)$
$w(d \otimes a) \succeq w(d \otimes b)$

Figure 3.3: *Graphical representation of right and left isotonicity.*

Isotonicity The algebra on top of $(S, \otimes, w, \succeq)$ is isotonic if $w(a) \succeq w\,(b)$ implies both $w(a \otimes c) \succeq w(b \otimes c)$ (right isotonicity) and $w(d \otimes a) \succeq w(d \otimes b)$ (left isotonicity). If the $\succeq$ is strictly $\succ$ we say that the metric is strictly isotonic.

Optimality Given a path weight structure $(S, \otimes, w, \succeq)$ and a path calculation algorithm R which returns a minimum path $R(a, b)\ \forall\ a, b \in S$, the routing protocol R is said to be optimal if, for any two distinct nodes a, b and for any path $p(a, b)$ connecting them, we have that $w(R(a, b)) \succeq w(p(a, b))$.

Consistency A routing protocol R on a path weight structure $(S, \otimes, w, \succeq)$ is consistent if for any couple of distinct nodes a, b, every node $v \in R(a, b)$ forwards packets to $\overrightarrow{S}(v, R(a, b))$, where $\overrightarrow{S}$ identifies the successor of node v on path $R(a, b)$.

3.3 TQ properties, the ideal case

B.A.T.M.A.N. belong to the distance vector family of routing protocols thus, according to [25], the routing metric must be left-monotonic and left-isotonic to ensure both optimality and consistency[1].

We start providing the demonstrations of isotonicity and monotonicity for the TQ metric assuming guaranteed delivery of management frames, for example using TCP at layer 3.

[1]We do not report the demonstration. The interested reader can refer to [25].

We know that B.A.T.M.A.N works at layer 2 using broadcast routing management frames that can get lost as they do not receive any physical acknowledgement. So we have to examine also what happens in a real scenario in presence of losses, trying to demonstrate the same properties in case of missing OGMs.

For clarity, in the rest of the chapter, instead of using the generic order relation $\succeq$, we will use the order relation $\geq$ because TQ values are expressed using real numbers.

3.3.1 Monotonicity

In an ideal situation without path OGM losses, OGM forwarding mechanism always reduces the TQ carried by OGM thus guaranteeing strict monotonicity. Given a path $\mathcal{P} = \langle o_1, \cdots, o_n \rangle$ having length $(n-1)$, and a path $\mathcal{Q} = \langle o_n, \cdots, o_{n+m} \rangle$ having length $(m-1)$. Strictly left monotonicity require:

$$TQ(\mathcal{P} \otimes \mathcal{Q}) < TQ(\mathcal{Q}) \tag{3.3}$$

Given the definition of path TQ in 3.2, we have that:

$$TQ(\mathcal{P}) = (1-\alpha)^{n-1} \times \prod_{i=1}^{n-1} TQ(o_i, o_{i+1})$$

and

$$TQ(\mathcal{Q}) = (1-\alpha)^{m-1} \times \prod_{j=n}^{m+n-1} TQ(o_j, o_{j+1})$$

and the TQ of the concatenated path is

$$TQ(\mathcal{P} \otimes \mathcal{Q}) = (1-\alpha)^{n+m-1} \times \prod_{i=1}^{m+n-1} TQ(o_i, o_{i+1})$$

Now we have to verify that 3.3 apply:

$$(1-\alpha)^{n+m-1} \times \prod_{i=1}^{m+n-1} TQ(o_i, o_{i+1}) < (1-\alpha)^{m-1} \times \prod_{j=n}^{m+n-1} TQ(o_j, o_{j+1})$$

and simplifying

$$(1-\alpha)^n \times \prod_{i=1}^{n-1} TQ(o_i, o_{i+1}) < 1$$

or

$$(1-\alpha) TQ(\mathcal{P}) < 1$$

Since $TQ(\mathcal{P}) \leq 1$ and $\alpha > 0$ the inequality is always true[2]. The particular case in which $TQ(\mathcal{P}) = 0$ or $TQ(\mathcal{Q}) = 0$ is not considered, as OGMs are discarded when TQ fields contains 0 (the path is considered as not existing). ■

The demonstration for left monotonicity is equivalent, so it is not reported. From this result it derives that TQ routing metric is strictly monotonic in the ideal case.

An interesting observation is the absolute necessity of a non zero HOP_-PENALTY factor (or a tie break rules that consider path length). Without HOP_PENALTY in fact the strict monotonicity could not be guaranteed since paths with no losses ($TQ = 1$) can exist.

3.3.2 Isotonicity

Again we analyse an ideal scenario with no path OGM losses. Consider two path from a to b, one is $\mathcal{P} = \langle a = o_1, \cdots, o_n = b \rangle$ having length n and a path $\mathcal{Q} = \langle a = v_1, \cdots, v_m = b \rangle$ having length m with $TQ(\mathcal{P}) < TQ(\mathcal{Q})$. We concatenate a path $\mathcal{R} = \langle b = s_1, \cdots, s_k \rangle$ having length k both to $\mathcal{P}$ and $\mathcal{Q}$. Strictly right monotonicity require that:

$$TQ(\mathcal{R} \otimes \mathcal{P}) < TQ(\mathcal{R} \otimes \mathcal{Q}) \tag{3.4}$$

As we have done with monotonicity demonstration, we take the definition of path TQ in 3.2, obtaining:

$$TQ(\mathcal{R} \otimes \mathcal{P}) = (1-\alpha)^{n+k-1} \times \prod_{i=1}^{k-1} TQ(s_i, s_{i+1}) \times \prod_{i=1}^{n-1} TQ(o_i, o_{i+1})$$

[2]Implementation takes into account operation precision and rounding to ensure at least unitary TQ decrease.

and

$$TQ(\mathcal{R} \otimes \mathcal{Q}) = (1-\alpha)^{m+k-1} \times \prod_{i=1}^{k-1} TQ(s_i, s_{i+1}) \times \prod_{i=1}^{m-1} TQ(v_i, v_{i+1})$$

Now we have to verify that 3.4 is valid:

$$(1-\alpha)^{n+k-1} \times \prod_{i=1}^{k-1} TQ(s_i, s_{i+1}) \times \prod_{i=1}^{n-1} TQ(o_i, o_{i+1}) < \\ (1-\alpha)^{m+k-1} \times \prod_{i=1}^{k-1} TQ(s_i, s_{i+1}) \times \prod_{i=1}^{m-1} TQ(v_i, v_{i+1})$$

so simplifying we have:

$$(1-\alpha)^{n-1} \times \prod_{i=1}^{n-1} TQ(o_i, o_{i+1}) < (1-\alpha)^{m-1} \times \prod_{i=1}^{m-1} TQ(v_i, v_{i+1})$$

that is equivalent to

$$TQ(\mathcal{P}) < TQ(\mathcal{Q})$$

This demonstrates strictly right isotonicity since $TQ(\mathcal{P}) < TQ(\mathcal{Q})$ was the initial assumption[3]. ■

Left isotonicity can be demonstrated in the same manner. We have verified that TQ metric is both strictly left and right isotonic.

3.3.3 Consistency and optimality

We have demonstrated that in absence of packet loss, the TQ metric is guaranteed to be both strictly monotonic and strictly isotonic. This fact guarantees, according to [25], that a protocol[4] using TQ as a metric, is consistent and optimal. As a consequence also loop-freeness is enforced.

We have demonstrated that an hypothetical B.A.T.M.A.N. implementation with guaranteed routing message delivery will work in a consistent way, without creating loops, and will be optimal with respect to TQ.

[3]A proper implementation is a key issue because of precision. In the actual source code only simple isotonocity is guaranteed.

[4]It is not necessary to specify the routing protocol type, because strict monotonicity and strict isotonicity guarantee optimality and consistency for all protocol families.

Incidentally we noticed that if OGMs are never lost the local Transmission Quality is deterministically 1. In this condition, the TQ metric collapses on a minimum hop metric, and the formal proof of consistency and optimality is just a validation.

We know that the actual implementation, however, uses level 2 broadcast to disseminate routing information. So we need to verify if this properties holds also in case of losses and, otherwise, if the protocol implements proper mechanism in order to maintain its consistency when losses occur.

3.4 The real implementation

OGM losses have an impact on B.A.T.M.A.N. routing protocol consistency and optimality. In particular we will see that, with the absence of guaranteed delivery of OGMs, B.A.T.M.A.N routing protocol cannot be optimal and consistent, independently from routing metric properties.

In absence of consistency, that would have implied loop freeness, we need to verify in a formal way if the protocol respect at least the fundamental properties of loop-freeness possibly employing ad hoc mechanisms.

We will focus our attention on forwarding rules, and on a special mechanism introduced to increase the reliability of OGMs that we called *fast OGM forwarding.* If a fresh OGM is received through a sub-optimal path, the OGM is rebroadcast with the current router TQ average, despite the OGM with that sequence number has been not received from the router.
We will see that this mechanism completely destroys monotonicity of the routing metric and, as a consequence, can cause also routing loops.

3.4.1 B.A.T.M.A.N. optimality and consistency

We want to verify the validity of consistency and optimality of B.A.T.M.A.N. routing protocol in case of path OGM losses, independently from metric properties such monotonicity and isotonicity.
Suppose the current best $\mathcal{P}$ path from a to node b to be:

$$\mathcal{P} = \mathcal{P}_1 \otimes \mathcal{P}_2 \qquad \begin{aligned} \mathcal{P}_1 &= \langle a = v_1, \cdots, v_k \rangle \\ \mathcal{P}_2 &= \langle v_{k+1}, \cdots, v_n = b \rangle \end{aligned}$$

Now a better new path $\mathcal{Q}$, partially overlapping with $\mathcal{P}$, becomes available:

$$\mathcal{Q} = \mathcal{Q}_1 \otimes \mathcal{Q}_2 \qquad \begin{aligned} \mathcal{Q}_1 &= \mathcal{P}_1 = \langle a = t_1 = v_1, \cdots, t_k = v_k \rangle \\ \mathcal{Q}_2 &= \langle t_{k+1} \neq v_k, \cdots, t_n = b \rangle \end{aligned}$$

Suppose $TQ(\mathcal{Q}_2) < TQ(\mathcal{P}_2)$, so the best path becomes $R(a,b) = \mathcal{Q}$. Now if the first path OGM travelling thought $\mathcal{Q}_2$ is lost at link from t_{k+1} to t_k, we have that $\overrightarrow{S}(v_k, R(a,b)) = v_{k+1} \neq t_{k+1}$ violating consistency definition.
In a similar situation the protocol is also sub-optimal because we have that $w(R(a,b)) \leq w(Q)$ thus violating optimality definition.

This situation of inconsistency and sub-optimality ends when an OGM will eventually traverse the entire path $\mathcal{Q}_2$. From this observation, it derives that B.A.T.M.A.N. routing protocol consistency and optimality are strictly related to the loss probability of global OGM messages. Given that the loss probability is less than 1, the protocol will eventually converge to a consistent and optimal configuration.

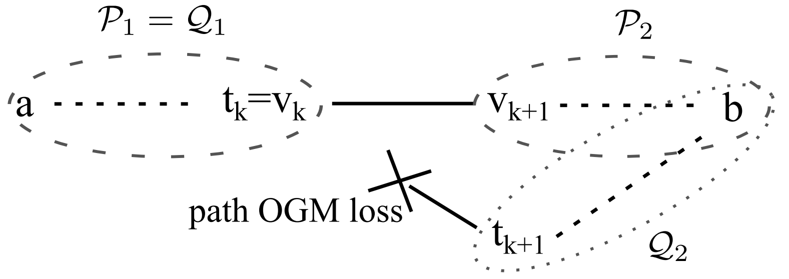


Figure 3.4: *Example of inconsistency caused by path OGM loss. In the picture $TQ(\mathcal{Q}_2) < TQ(\mathcal{P}_2)$ but the path update does not reach node v_k causing inconsistency.*

3.4.2 TQ window and monotonicity violation

B.A.T.M.A.N. does not use directly received TQ values, but it averages theme on a sliding window measured in number of samples. Missing values (those corresponding to OGM losses) are simply not considered in the average.

The average is used for routing decision, and it is also broadcast to neighbours when the fast OGM forwarding mechanism triggers. As a consequence, it is necessary to verify whether this particular average together with protocol forwarding rules, still preserves monotonicity or not.

Consider a chain of n nodes $\langle v_1, v_2, \cdots, v_n \rangle$. Every node v_i maintain the average TQ toward v_1 via neighbour v_{i-1}, indicated with $\overline{TQ}_{v_{i-1}}(v_1)$ calculated using TQ values received in OGMs traversing the chain.

The average is calculated using values of latest TQ_GLOBAL_WINDOW_SIZE (indicated with w) OGMs. So, supposing the latest sequence number received was k, we can write TQ toward node v_1 of node v_i (via neighbour v_{i-1}) as:

$$\overline{TQ}_{v_{i-1}}(v_i, v_1) = \frac{\sum_{j=k-w}^{k} TQ^j_{v_{i-1}}(v_i, v_1)}{w}$$

Monotonicity in this case require:

$$\overline{TQ}_{v_{i-1}}(v_i, v_1) > \overline{TQ}_{v_i}(v_{i+1}, v_1) \tag{3.5}$$

Absence of packet losses

Given that TQ values are monotonically decreasing, it is easy to verify that, in case of absence of packet losses, inequality 3.5 holds since:

$$\overline{TQ}_{v_i}(v_{i+1}, v_1) = \frac{\sum_{j=k-W}^{k}(1-\alpha)TQ(v_{i+1}, v_i)TQ^j_{v_{i-1}}(v_i, v_1)}{w}$$

so

$$\overline{TQ}_{v_i}(v_{i+1}, v_1) = (1-\alpha)TQ(v_{i+1}, v_i)\overline{TQ}_{v_{i-1}}(v_i, v_1) < \overline{TQ}_{v_{i-1}}(v_i, v_1)$$

and given $\alpha < 1$ and $TQ(v_{i+1}, v_i) \leq 1$, monotonicity is verified. ■

Presence of packet losses

Now suppose OGM with sequence number s with $s < k$ and $s > k - W$ was not received by node v_{i+1}. We know that $\overline{TQ}$ is calculated only on received values ignoring packet losses, in other word the average is calculated summing received TQ values and dividing by ($w - losses\#$). In this case we have that $losses\# = 1$. Now we have to verify that 3.5 is still valid. We can write:

$$\overline{TQ}_{v_{i-1}}(v_i, v_1) > (1-\alpha)TQ(v_{i+1}, v_i)\left[\frac{\sum_{j=k-W}^{k} TQ^j_{v_{i-1}}(v_i, v_1) - TQ^s_{v_{i-1}}(v_i, v_1)}{w-1}\right]$$

that is equivalent to

$$\frac{w-1}{w}\overline{TQ}_{v_{i-1}}(v_i,v_1) > (1-\alpha)TQ(v_{i+1},v_i)\left[\frac{\sum_{j=k-W}^{k} TQ^{j}_{v_{i-1}}(v_i,v_1)}{w} - \frac{TQ^{s}_{v_{i-1}}(v_i,v_1)}{w}\right]$$

so

$$\frac{w-1}{w}\overline{TQ}_{v_{i-1}}(v_i,v_1) > (1-\alpha)TQ(v_{i+1},v_i)\left[\overline{TQ}_{v_{i-1}}(v_i,v_1) - \frac{TQ^{s}_{v_{i-1}}(v_i,v_1)}{w}\right]$$

finally obtaining

$$TQ^{s}_{v_{i-1}}(v_i,v_1) > \left(\frac{w(1-\alpha)TQ(v_{i+1},v_i)-w+1}{(1-\alpha)TQ(v_{i+1},v_i)}\right)\overline{TQ}_{v_{i-1}}(v_i,v_1)$$

and simplifying

$$TQ^{s}_{v_{i-1}}(v_i,v_1) > \overline{TQ}_{v_{i-1}}(v_i,v_1)\left(w - \frac{w-1}{(1-\alpha)TQ(v_{i+1},v_i)}\right)$$

We know that TQ values express probabilities so they are in the interval $]0,1]$ (the case of $TQ = 0$ cannot happen as OGM would be discarded). So given $TQ^{s}_{v_{i-1}}(v_i,v_1) \in]0,1]$ a necessary and sufficient condition can be derived:

$$\overline{TQ}_{v_{i-1}}(v_i,v_1)\left(w - \frac{w-1}{(1-\alpha)TQ(v_{i+1},v_i)}\right) \leq 0$$

simplifying we obtain:

$$TQ(v_{i+1},v_i) \leq \frac{w-1}{(1-\alpha)w}$$

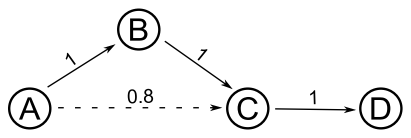
which clearly is not guaranteed to be always satisfied for every value α and w. So we have demonstrated that in case of OGM losses monotonicity is not always verified. ■

3.4.3 Fast OGM forwarding and loops

The *Fast OGM forwarding* mechanism is strictly related to the TQ average. In case a fresh OGM arrives from a sub-optimal path, the average path TQ of the router is forwarded with the fresh sequence number. We have demonstrated that even a single packet loss can violate monotonicity of the TQ average, as illustrated in figure 3.5. The situation becomes even worse in case of multiple OGM losses that happen for example when a node breaks or moves out of range in a mobile network. In these situations the protocol can form also routing loops.

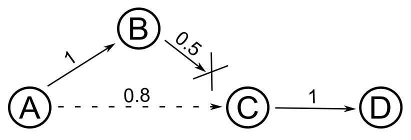
Consider a path $\mathcal{P} = \langle v_1, v_2, \cdots, v_i, \cdots v_n \rangle$, and suppose that OGM with sequence number s is not received by node v_i from node v_{i-1}, but from a sub-optimal path. At this point v_i immediately forward the OGM with the average TQ of the optimal path $\langle v_i \cdots v_n \rangle$ thanks to the fast OGM forwarding mechanism. Suppose the TQ contained in the missing OGM caused a TQ average monotonicity violation, as described in previous section. At this point, node v_{i+1} will receive a TQ for path $\langle v_{k-1} \cdots v_n \rangle$ which is greater than the actual TQ of $\langle v_k \cdots v_n \rangle$ violating monotonicity.

In case of multiple losses, or link breakage, the monotonicity violation can cause routing loops as described in figure 3.6. The loop described is not persistent and it is resolved as soon as TQ of OGM in the loops drops under the TQ of a loop-free alternative route.



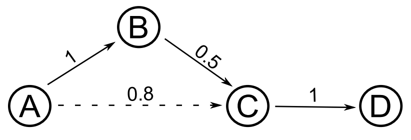
$$\overline{TQ}_b(c,a) = 0.98 \times \frac{1+1+1+1+1}{5} = 0.980$$

$$\overline{TQ}_c(d,a) = 0.98^2 \times \frac{1+1+1+1+1}{5} = 0.960$$



$$\overline{TQ}_b(c,a) = 0.98 \times \frac{1+1+1+1+\bullet}{4} = 0.980$$

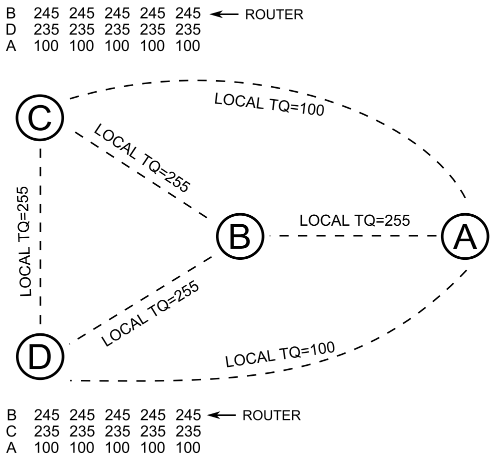
$$\overline{TQ}_c(d,a) = 0.98^2 \times \frac{1+1+1+1+1}{5} = 0.960$$



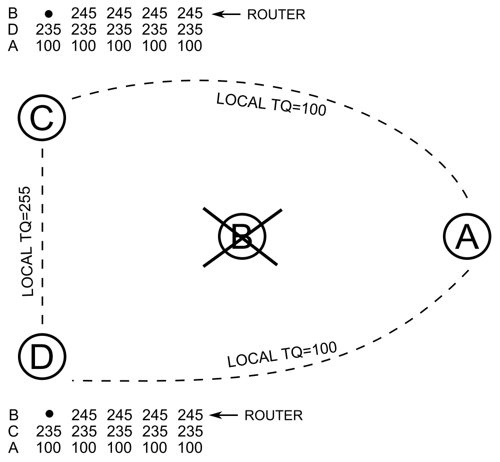
$$\overline{TQ}_b(c,a) = 0.98 \times \frac{1+1+1+\bullet+0.5}{4} = \mathbf{0.858}$$

$$\overline{TQ}_c(d,a) = 0.98^2 \times \frac{1+1+1+1+0.5}{5} = \mathbf{0.864}$$

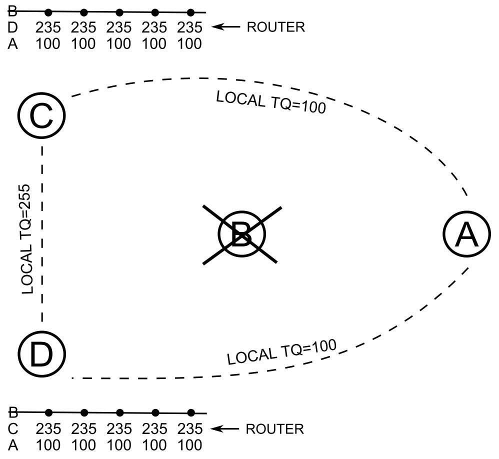
Figure 3.5: *Scenario in which monotonicity is violated. On the left are indicated local TQs evolution and is represented with arrows the path OGMs flow. On the right the $\overline{TQ}$ calculation toward node A from node C and D is reported. Example values $\alpha = 0.02$ and windows size $w = 5$ are used.*
It can be seen that broadcasting the average calculated ignoring lost OGMs, can lead to monotonicity violation. In particular node D results to have a better TQ toward station A than node C.



At the beginning, both nodes C and D have B as best route toward originator A.



Node B breaks. Both nodes C and D still receive OGMs directly from A and start forwarding average TQ of the old optimal path.



As soon as a number of OGMs equal to windows size are missing from B, the station B is removed from C and D routing tables. At this point a loop involving nodes C and D is created.

Figure 3.6: *Scenario in which a routing loop occurs caused by the forwarding of average TQ values even if OGMs are not received from the best path. The evolution of TQ window toward originator A at nodes C and D is shown in case of failure of node B. After a time equal to TQ_GLOBAL_WINDOW_SIZE × OGM_INTERVAL the loop involving nodes C and D is formed.*

Chapter 4

Enforcing loop-freeness for B.A.T.M.A.N.

Loop freeness is a fundamental characteristic of whatever routing protocol, so we want to enforce it for B.A.T.M.A.N. because, as we have seen, with the current implementation routing loops can occur.

The ingredients necessary to obtain this important properties already exist, they are TQ monotonicity and sequence number of routing management frames. Putting together this ingredients in the right way, we can obtain and demonstrate loop-freeness.

We will propose two different approach to the problem. The first is the most intuitive one, but introduce routing tables instability that lead to route flapping. We then describe another approach that introduce strict forwarding rules similar to the ones implemented in DSDV [23], and guarantees both routing stability in case of losses and loop freeness.

4.1 Assigning zero TQ to lost OGMs

The simplest way to guarantee monotonicity is to take into account lost packets in the average assigning a $TQ = 0$. In this way it is simple to verify that 3.5 is valid also in case of packet losses. In fact, in case OGM with sequence number s, with $s < k$ and $s > k - W$, was not received by node v_{i+1}, we have

$$\overline{TQ}_{v_{i-1}}(v_i, v_1) > (1-\alpha)TQ(v_{i+1}, v_i)\left[\frac{\sum_{j=k-W}^{k} TQ^{j}_{v_{i-1}}(v_i, v_1) - TQ^{s}_{v_{i-1}}(v_i, v_1)}{w}\right]$$

and simplifying we obtain

$$\overline{TQ}_{v_i}(v_{i+1}, v_1) > (1-\alpha)TQ(v_{i+1}, v_i)\overline{TQ}_{v_{i-1}}(v_i, v_1) - \frac{TQ^s_{v_{i-1}}(v_i, v_1)}{w}$$

that can be written as

$$\overline{TQ}_{v_i}(v_{i+1}, v_1) > \overline{TQ}_{v_i}(v_{i+1}, v_1) - \frac{TQ^s_{v_{i-1}}(v_i, v_1)}{w}$$

finally obtaining

$$\frac{TQ^s_{v_{i-1}}(v_i, v_1)}{w} > 0$$

and given $w > 0$ and $TQ^s_{v_{i-1}}(v_i, v_1) > 0$ monotonicity is verified. ■

4.1.1 Drawbacks

Apart from the mixing of purposes of path OGMs and link OGMs that complicates the protocol analysis, a similar implementation could cause an imbalance in the TQ calculation. A single path OGM loss in fact would directly influence the TQ of the path in a dominant way, with respect to an analogue link OGM loss. This is because TQ_LOCAL_WINDOW_SIZE is much greater than TQ_GLOBAL_WINDOW_SIZE [1]. It can also happen that two paths traversing the same sequence of links would have different TQ values, and this can create instability and logical inconsistencies.

Furthermore this approach results to be too aggressive in reducing path quality perception due to even a single packet loss, inevitably causing frequent unnecessary route changes. In this way also sub-optimal paths results to be chosen, thus degrading the overall protocol performance.

4.2 Removing global window and fast OGM forwarding

A solution that guarantees loop-freeness without influencing the routing metric, and without causing instability problems is desirable. To obtain this results we

[1]Default values of TQ_LOCAL_WINDOW_SIZE and TQ_GLOBAL_WINDOW_SIZE are respectively 64 and 5.

have divided our modification in two steps.

We start removing TQ average that, as we have seen, in case of losses produces a monotonicity violation. In place of the average, we consider only the latest received TQ value that better reflects the actual path quality.

In the second phase we define stricter OGM forwarding rules based on sequence number partially derived from those defined in DSDV. Finally we add the principle of not creating *artificial OGMs* as the fast OGM forwarding mechanism did. To increase routing management frames reliability, we propose another mechanism that respects forwarding rules and did not alter metric calculation and protocol properties.

4.2.1 Why average is not necessary

Averaging path TQ has been considered as necessary to stabilize oscillation in the TQ values, typical of wireless links that can exhibit time-varying characteristics. In reality an averaging is already done in local link TQ evaluation given that it is calculated using a sliding window.

We think also that mechanism using moving average, as those proposed for future protocol versions, must be applied only on link basis to identify in a faster way broken or unstable links. Calculating moving average on path TQs does not have any sense because variations are very slow due a previous slow averaging of link TQs that are combined to obtain the resulting path TQ.

4.2.2 Update of path TQ

Any node v maintains, for every originator o, the freshest sequence number $s(o)$ received via whatever path. In addiction the node memorizes the greatest OGM sequence number of o received from each candidate router n, indicated with $s_n(o)$. Formally we have:

$$s(o) = \max_n(s_n(o)) \tag{4.1}$$

The TQ toward originator o via neighbour n is defined as the TQ contained in the latest (in term of sequence number) OGM of o received from n. A broken path via router n is identified if MAX_SEQNO_GAP (indicated with g) consecutive OGMs of o have not been received via n.
Formally the path TQ toward o via neighbour n, written as $\widehat{TQ}$, to differentiate

the notation from previous average $\overline{TQ}$, can be written as:

$$\widehat{TQ}_n(v,o) = \begin{cases} 0 & \text{if } s_n(o) < s(o) - g, \\ TQ_n^{s_n(o)}(v,o) & \text{otherwise.} \end{cases} \tag{4.2}$$

The parameter MAX_SEQNO_GAP can be tuned to balance between route stability and fast reaction on failure. Opportunely setting OGM_INTERVAL and MAX_SEQNO_GAP, we can regulate the protocol convergence speed in case of topology modifications or node failures. For example in an infrastructure mesh network, where mesh router are fixed, it is opportune to assign higher OGM_INTERVAL and MAX_SEQNO_GAP to reduce protocol overhead and maximize stability since topology changes and failures are rare. On the other hand, in a client WMN it is opportune to set low OGM_INTERVAL and MAX-_SEQNO_GAP thus obtaining a rapidly reactive protocol.

A mechanism to dynamic tune this parameters could be implemented to automatically adapt to different network situations, without requiring the user intervention. This could be an important improvement for obtaining a more flexible and adaptive protocol, representing an interesting research topic.

4.2.3 Route change feasibility

To avoid the creation of routing loops, route changes can happen only if certain requisites are respected. Before any route change we check sequence number and TQ values to ensure particular condition that will guarantee loop-freeness.

Indicating with r the current router toward a node v, a route change from r to a candidate router n can occur only if an OGM with fresh sequence number $s_n(o) \geq s(o)$ is received from n and if $TQ_n(v) > TQ_r(v)$.

From these rules, we can derive a new formal order relation $\succ$ on $\widehat{TQ}$:

$$\widehat{TQ}(\mathcal{P}) \succ \widehat{TQ}(\mathcal{Q}) \iff \Big(s(\mathcal{P}) \geq s(\mathcal{Q})\Big) \wedge \Big(\widehat{TQ}(\mathcal{P}) > \widehat{TQ}(\mathcal{Q})\Big) \tag{4.3}$$

The implementation of this new order relation modifies OGM processing and forwarding rules.

An OGM received from originator o via neighbour n and sequence number j, according to our notation carries the information $TQ_v^j(o)$.
The OGM is discarded if $j < s_n(o)$ because, according to 4.2, it does not modify any TQ. In the other case, the OGM is processed, causing a modification of the current path TQ via n, and possibly triggering a router change. Indicating with

r the current router, we have 2 cases in which an OGM is forwarded:

- if $n = r$ and $j > s_n(o)$ forward the OGM updating the TQ field.
- if $n \neq r$, $j \geq s(o)$ and $TQ_n(o) > TQ_r(o)$, from 4.3 we have that $TQ_n(o) \succ TQ_r(o)$, so change router to n and forward the OGM updating the TQ field.

The forwarding process maintains monotonicity of forwarded values and guarantee also loop freeness as we will demonstrate in the next section.

4.2.4 Monotonicity

Using the novel TQ calculation algorithm, together with new forwarding rules, packet losses do not destroy monotonicity so loop-freeness is guaranteed. In a chain of n nodes $\langle v_1, v_2, \cdots, v_n\rangle$, every node v_i maintain the path TQ toward v_1 via neighbour v_{i-1}, indicated with $\widehat{TQ}_{v_{i-1}}(v_1)$. From 3.3 we have to verify that:

$$\widehat{TQ}_{v_{i-1}}(v_i, v_1) \succ \widehat{TQ}_{v_i}(v_{i+1}, v_1) \qquad (4.4)$$

Without packet losses, the demonstration derives directly from simple TQ monotonicity, since we compare single TQ values with the same sequence number.
Instead if an OGM of node v_q with sequence number j is lost at link (v_i, v_{i+1}), we have two cases:

- $j = s_{vi-1}(o) qquad$ no route monotonicity violation occurs because nodes v_{i+1} will have a sequence number $s_{vi}(o) < s_{vi-1}(o)$. So in any case we have from 4.3 that $\widehat{TQ}_{v_{i-1}}(v_i, v_1) \succ \widehat{TQ}_{v_i}(v_{i+1}, v_1)$
- $j < s_{vi-1}(o) qquad$ a fresher OGM has been already received by node v_{i+1}. The monotonicity is demonstrated as in the loss free case because the latest OGM, used in the $\widehat{TQ}$ calculation has been correctly received.

So the novel order relation on $\widehat{TQ}$ metric is guaranteed to be monotonic also in case of losses. ■

4.3 Loop-freeness proof

According to [25], monotonicity is a sufficient condition for guarantee loop-freeness. In this section we provide a simple direct demonstration of loop-freeness to better clarify all the concepts.

Consider a network composed of N nodes in a situation without routing loops. Lets consider a node n in the network and an originator o with $o \neq n$. A list of candidate neighbour router $[r_1, \cdots, r_m]$ is maintained, together with the freshest sequence number received from each candidate indicated with $s_{r_j}(o)$. The current router is indicated with $R(o)$, and the current router TQ with $\widehat{TQ}_r(o)$.
Now an OGM of originator o is received via router r_j with sequence number k. The case in which $R(o) = r_j$ is not considered because no route changes can occur, so we consider only the case $R(o) \neq r_j$. Now there are 3 possibility that need to be analysed:

- If $k < s(o)$ the packet is considered old and is discarded, so no routing loop is created.
- If $k >= s(o)$ and $TQ^k_{r_j}(o) <= \widehat{TQ}_r(o)$ no route change occurs, so no routing loop is created.
- If $k >= s(o)$ and $TQ^k_{r_j}(o) > \widehat{TQ}_r(o)$ the router become r_j and no routing loop is created because of TQ monotonicity. In fact an hypothetical loop cannot be closed at node n because the OGM message with sequence number k has not been seen before.

The loop freeness property is demonstrated giving the necessary solid theoretical basis to B.A.T.M.A.N. routing protocol that until now was missing. ■

4.3.1 New OGM fast forwarding

The fast OGM forwarding mechanism has the primary purpose of increasing the reliability of OGM since they can get lost along a path with a non negligible probability, especially if the path is long. Actually the benefits deriving from the fast OGM forwarding mechanism have not been analysed in a rigorous way. In particular given the presence of sliding windows in the previous version, and of the MAX_SEQNO_GAP in the new implementation, probably this mechanism is not necessary. Anyhow there exist a benefit in the boot-strap phase, as the initial propagation of originator information is faster, so we decide to rewrite this mechanism and apply it also in the modified protocol version.

To substitute this mechanism, a more safe (in term of routing protocol properties) approach can be used. If for a certain originator o with router r it is $s_r(o) < s(o) - 1$, the old router OGM with sequence number $s(o) - 2$ can be rebroadcast thus increasing reliability in case of lossy paths.

Clearly this approach does not have any impact on routing protocol properties, because no new message is created. The station can only rebroadcasts an old (in term of sequence number) OGM, that was already sent, without modifying any field of the original message. Finally we have that if the receiving nodes had already seen that OGM, it simply discards the packet, while if the OGM is new the station registers the OGM that was previously got lost.

Chapter 5

Results in emulated network and in real test-bed

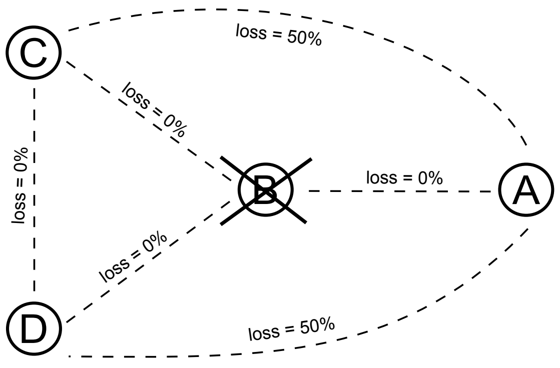


Figure 5.1: *Simple topology used in the simulation. At the beginning node 2 is the router for nodes 3,4 to node 1. When it breaks routing loops occurs using the standard implementation.*

To demonstrate the benefits of the proposed modification and effectively show that the current B.A.T.M.A.N. implementation can cause routing loops, a series of simulations, using both virtual machines and real devices, have been done on the simple topology depicted in figure 5.1.

What we want to verify is the formation of routing loops in case of node failures and measure the relationship between loop duration and parameters such as HOP_PENALTY and TQ_GLOBAL_WINDOW_SIZE that, as we have seen, are strictly related to routing metric monotonicity. The duration of a loop has an impact on protocol convergence on a novel stable route in case of failure and also in case of node mobility. The slow recovery after node failure of B.A.T.M.A.N. has been also reported in [26], but the authors did not investigate on the causes originating this problem.

Details about tools and techniques used in the emulation are reported in the appendix A.

5.1 Test connectivity

In our simulation, we have to monitor connectivity between a given pair of nodes, or better, the presence of a valid route between the nodes. We have used ICMP echo packets, using the ping utility, to sample connectivity opportunely reducing the interval between consecutive ping rounds to obtain the desired time granularity.

To formalize following analysis we define the function ICMP(k) as a function on the reception of ICMP echo reply with a given sequence number. The function is defined as follow:

$$\text{ICMP}(k) = \begin{cases} 0 & \text{if ICMP reply with sequence number } k \text{ has not been received} \\ 1 & \text{otherwise.} \end{cases} \tag{5.1}$$

When the ICMP function has value 1, it means that in that time instant a valid route exists between the analysed pair of nodes, while if ICMP(k) = 0 there isn't a valid route between nodes.

In all graphics reporting the obtained results, the ICMP packet numbers are normalized to have node break instant corresponding to ICMP packet having sequence number 0.

5.2 Sample run

The results obtained from the simulation shows a tendency of the standard B.A.T.M.A.N. implementation to become unstable after the failure. This phase causes a variable connectivity between node A and nodes C, D. A sample run, given the ICMP function definition in 5.1, is reported in figure 5.2.

This is not the expected behaviour, because in addition to a delay caused by the formation of routing loop, there is also a successive phase of instability that causes inconstant connectivity. Given this behaviour it become difficult to measure the convergence time. In particular we cannot say that the routing protocol has converged upon the reception of the first ICMP response after node B failure.

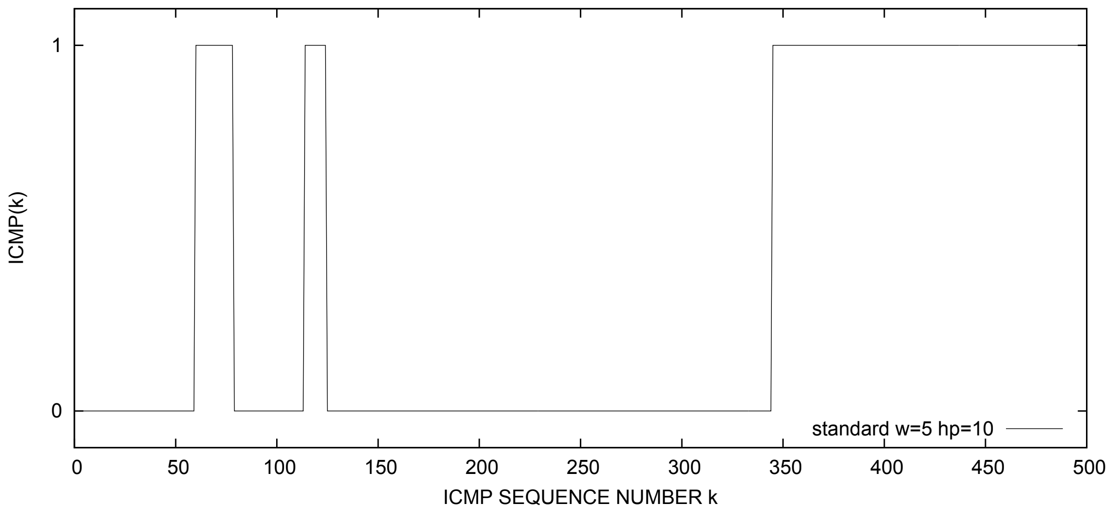


Figure 5.2: *Sample run of standard protocol with basic setting of parameters TQ_GLOBAL_WINDOW_SIZE and HOP_PENALTY. Inconstant connectivity after B failure, corresponding to ICMP sequence number* 0*, is visible.*

An explanation of this unexpected behaviour emerges from a more careful analysis of the protocol implementation. We have logically distinguished local OGMs from path OGMs, but in the real implementation there is not any separation. So we have that local OGMs received from neighbours are always forwarded even if the direct link is not used as preferred route. In the emulated topology we have that direct links A-C and A-D are sub-optimal paths, so the described problem can produce inconsistencies in windows that produce the observed instability.

This problem has been resolved adding a flag to forwarded local OGM packets, indicating whether or not they are also to be considered as actual path OGMs. Anyhow all the experiments have been executed without applying this fix in both standard version and modified one, in order to not influence the experiments outcome.

5.3 Convergence time in case of node failure

We start measuring the convergence time in case of failure of node B in the topology illustrated in figure 5.1. Given the protocol instability registered during tests, that caused instability in the connection after the individuation of a new route toward node A, we have introduced a particular definition of protocol convergence. The convergence time is defined in term of the time necessary to observe a continuous and stable connectivity, lasting for a minimum amount of time.

Denoting with δ_{ICMP} the ICMP interval, and with ICMP(k) the outcome of ICMP request as defined in 5.1, we define k_0 as the sequence number of the first missing reply after node failure, while k_1 denotes the first received reply after node failure. The failure sequence number interval is defined as:

$$\Delta_0 = k_1 - k_0$$

Now the convergence time is defined as:

$$T_c = \delta_{\text{ICMP}} \times \Big(min(k) \; s.t. \; (\text{ICMP}(k) = 1 \; \forall \, k \in [k, k + 2\Delta_0]) \Big) \tag{5.2}$$

In other words, we define the protocol as converged if a number of ICMP replies equal to double the failure interval have been correctly received in a row. This function does not come from a rigorous analysis of the behaviour of the ICMP function after failure, but is intended as a fair way to deal with protocol instability.

5.3.1 Batch means and confidence interval

The purpose of our test is to estimate the average convergence time using the standard TQ calculation algorithm and compare it with the modified one. Experiment outcomes are maintained independent waiting a sufficient time between two consecutive tests to let all nodes converge to a stable situation. Anyhow we want to safely calculate confidence intervals, and thus we have used the batch mean method.

Indicating with X the random variable representing the convergence time obtained from our experiments, we divide our series of N results in k batches of equal size $m = \frac{N}{k} = \sqrt{n}$. Then we calculate the batch means:

$$\overline{Y}_j = \frac{1}{m} \sum_{i=1}^{m} X_{(j-1)b+i}, \qquad j = 1, 2, \ldots, k$$

Estimators $\overline{Y}_j$ are independent and identically distributed random variables if m is greater than any autocorrelation “mixing period”:

$$E\left[\overline{Y}_j\right] = \frac{1}{k} \sum_{j=1}^{k} \overline{Y}_j$$

which is equal to the value $E[X]$.

Now we can calculate the unbiased variance of $\overline{Y}_j$ that is:

$$\text{Var}\left[\overline{Y}_j\right] = \frac{1}{k-1}\sum_{j=1}^{k}\left(\overline{Y}_j - E\left[\overline{Y}_j\right]\right)^2$$

At this point we can safely construct confidence interval using a t-student distribution with $m-1$ degree of freedom taking $\sigma_Y = \sqrt{Var\left[\overline{Y}_j\right]}$. With a confidence level a we have that:

$$E[X] - t_{a,m-1}\frac{\sigma_Y}{\sqrt{m}} \leq \mu \leq E[X] + t_{a,m-1}\frac{\sigma_Y}{\sqrt{m}}$$

We have executed $N = 100$ tests and divided in 10 batches each containing 10 values. The confidence level used is 99%, so we have $t_{a,m-1} = t_{0.01,9} = 3.25$ so substituting we obtain:

$$E[X] - 3.25\frac{\sigma_Y}{\sqrt{10}} \leq \mu \leq E[X] + 3.25\frac{\sigma_Y}{\sqrt{10}}$$

These intervals are wider than the ones that can be calculated using directly X, but in this way we exclude any potential hidden autocorrelation between tests.

5.3.2 Dependence on TQ_GLOBAL_WINDOW_SIZE

The value TQ_GLOBAL_WINDOW_SIZE (or MAX_SEQNO_GAP in the modified version) regulates the dimension of the window containing path TQ values. This dimension is strictly related to route recovery time since a route is declared as broken when TQ_GLOBAL_WINDOW_SIZE consecutive OGMs have not been received via that route.

Actually this parameter of the protocol is not tunable by the user at runtime, but it is hard coded. This heavily limits the possibility of changing the protocol behaviour, for example when the network is highly dynamic. The only way to accelerate the protocol convergence remains the decrease of OGM_INTERVAL, at the cost of a major protocol overhead.

Despite this, we want to analyse the behaviour of the protocol using different window size. In fact we have seen that window size has a correlation with TQ average monotonicity, so we expect a proportional relation between loop duration and window size. This relation is confirmed in our simulation as can be seen in picture 5.3. An increase in window size generates an increase of convergence time due to an increase in the necessary time to identify a broken path, and also due

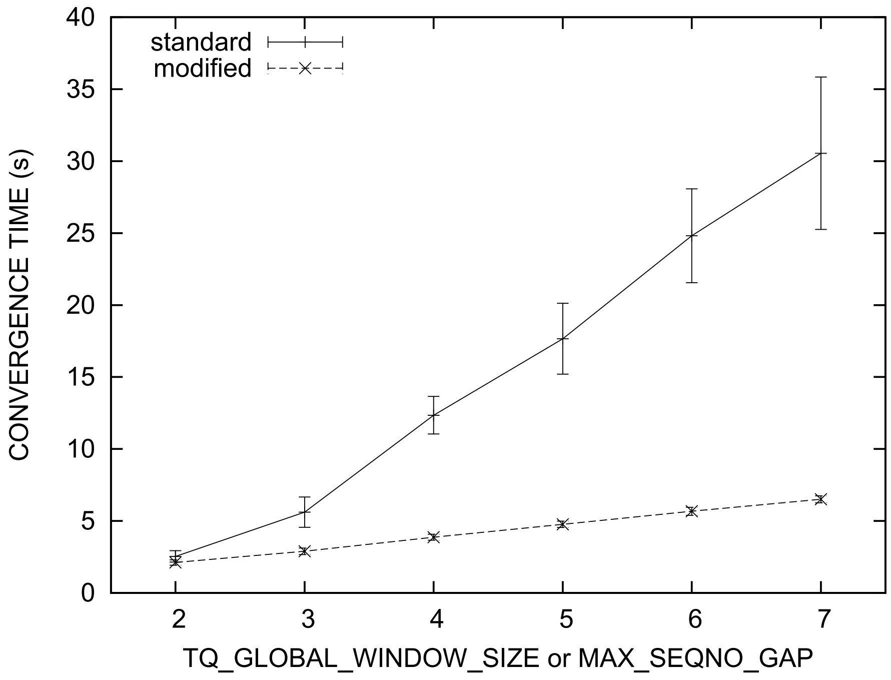


Figure 5.3: *Average convergence time in case of node failure varying TQ_GLOBAL_WINDOW_SIZE for standard B.A.T.M.A.N., and MAX_SEQNO_GAP in the modified version.*

to an increase in the routing loop duration.

The proposed loop free version of the protocol instead show a linear dependency between MAX_SEQNO_GAP and convergence time and, as expected, does not present any loop problem.

The current default value of TQ_GLOBAL_WINDOW_SIZE is 5 but given the result of simulation, we suggest to reduce it in order to partially reduce the loop duration and ameliorate the protocol convergence speed. This derive also from the observation that is quite improbable to miss 5 OGMs in a row, especially given the implementation of an OGM recovery mechanism in both protocol version.

Dependence on HOP_PENALTY

The parameter HOP_PENALTY is tunable in order to regulate the protocol behaviour in case of routes having similar TQ values but different lengths. An high value of HOP_PENALTY makes the metric similar to hop-count, while little values gives more importance to the actual transmission success probability of a route, neglecting its length.

In case of loop, HOP_PENALTY guarantees that the loop eventually will disappear, because *TQ* will diminish with each successive OGM travelling the

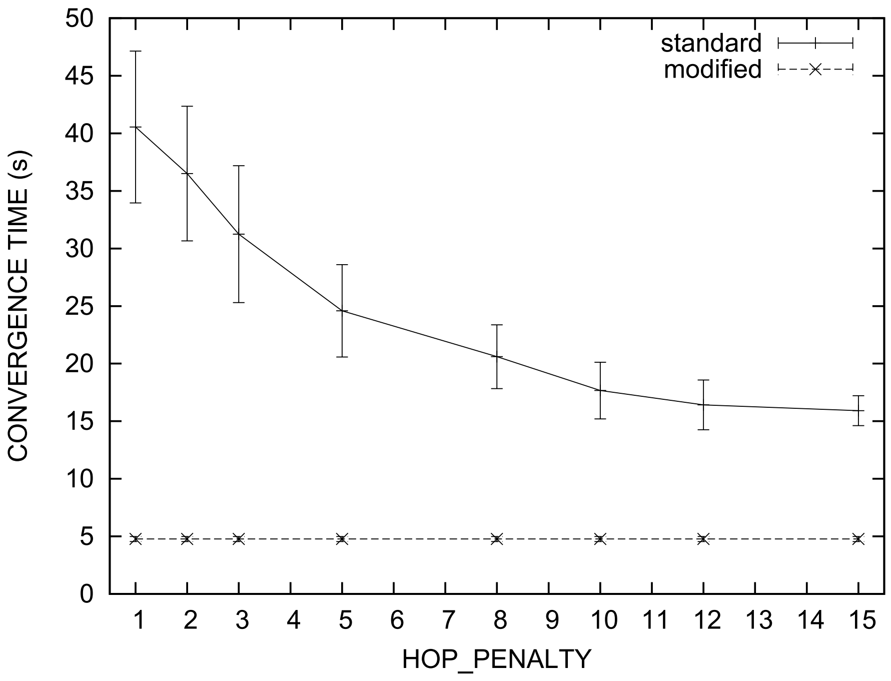


Figure 5.4: *Average convergence time in case of node failure varying the HOP_PENALTY value.*

loop. So the loop duration should be inversely proportional to HOP_PENALTY.

We have tested values of HOP_PENALTY ranging from 1, which is the minimum admissible value, to 15, that is quite an high value for a WMN routing protocol metric. In fact it does not make sense to test higher HOP_PENALTY values since the metric will become essentially hop-count. The behaviour of the two protocol versions is documented in figure 5.4. A relation between standard protocol implementation convergence time and HOP_PENALTY is evident. On the other hand the modified protocol does not present loop problems so convergence time is stable.

The modification of the HOP_PENALTY parameter should only influence the protocol bias against long route, as in the modified version. It is not acceptable, for the final user, that a modification of this parameter will alter the protocol convergence time.

5.4 ICMP response percentage

To obtain a more precise overview of the protocol behaviour after failure, and evidence the presence of a routing loop we can examine the percentage of ICMP response received after the failure of node B.

This value is calculated averaging the outcome of the function $ICMP(k)$ defined above for a big number of tests. To do this, the ICMP sequence number of different tests has been normalized assigning a sequence number of 0 to the first missing response after B failure.
Indicating with $\mathrm{ICMP}_i(k)$ the outcome obtained from the i-th test and being N the number of tests we define this measure as:

$$\varphi(k) = \frac{\sum_{i=1}^{N} \mathrm{ICMP}_i(k)}{N}$$

In this way we obtain the fraction of correctly received ICMP response for any ICMP normalized sequence number, starting from $k = 0$ that corresponds to node break. When this average reaches 1, it means that in all the runs the ICMP reply having sequence number k has been always received, so the protocol has converged in all the runs.

5.4.1 Dependence on TQ_GLOBAL_WINDOW_SIZE

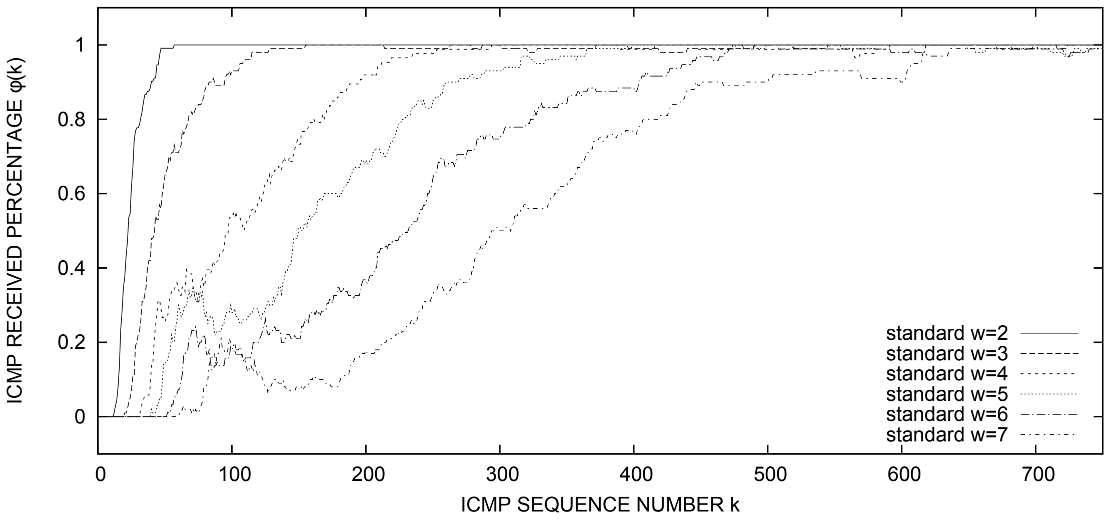


Figure 5.5: *Probability of successful ping after node failure at time $t = 0$ varying the TQ_GLOBAL_WINDOW_SIZE on the standard implementation.*

In figure 5.5 can be observed that the function $\varphi(k)$ converges more rapidly to 1 as the dimension of the TQ windows size is reduced, confirming that the mean convergence time is proportional to the window dimension.
The function for the modified version show that the modified protocol converges immediately after dropping the route via B and receiving an OGM from the alternative path. The standard version instead clearly shows an instability period

after dropping the broken route. This is due to the formation of a temporary loop that blocks connectivity.
Both version anyway converges on a stable route with all TQ_GLOBAL_WINDOW_SIZE values. In fact in any case the $\varphi(k)$ function reaches 1.

5.4.2 Dependence on HOP_PENALTY

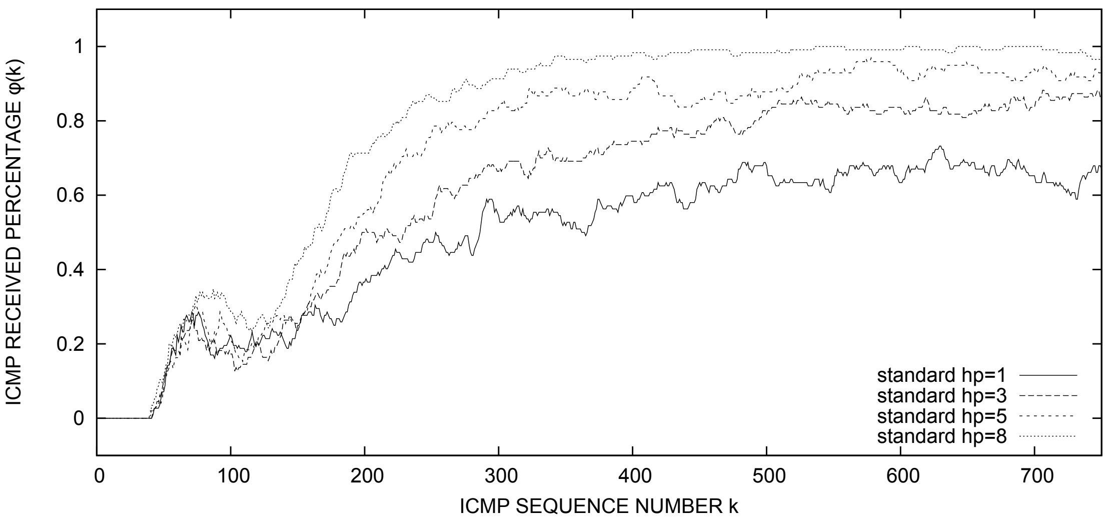


Figure 5.6: *Probability of successful ping after node failure varying the HOP_PENALTY value in the standard implementation.*

Differently from the window size variation, a modification of the HOP_PENALTY parameter influences not only the convergence time, but also the standard protocol stability. From the graph reported in figure 5.6, we can observe that assigning small value to HOP_PENALTY, the function $\varphi(k)$ does not reach 1, even after a long time after failure.
This means that even in a fixed topology without failure or node mobility routing inconsistencies can happen using low HOP_PENALTY values. This behaviour is probably related also to the misbehaviour described in section 5.2.

This result reflects the measurements done on convergence time, and confirms the existence of a major problem of the routing protocol. In fact, in the current implementation, an important parameter, tunable at runtime, influences not only the protocol behaviour as the user will expect, but also causes the protocol to become unstable, thus reducing the protocol performance even in a static topology.

5.5 Real test-bed

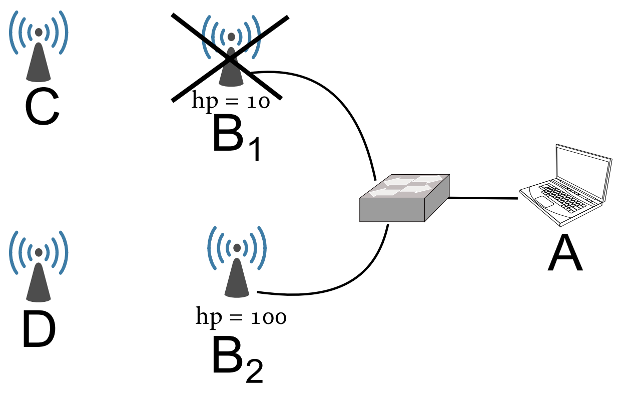


Figure 5.7: *Test-bed used for node failure experiments. To simulate a sub-optimal path an HOP_PENALTY factor of* 100 *has been set on node* B_2.

To validate the results obtained in the emulated network, we have built a real test-bed using off-the-shelf devices. In order to compare results obtained in the real world with the one obtained using emulators, we have built a topology very similar to the one implemented in the emulation environment (see figure 5.1).

Clearly it is difficult to obtain exactly the same situation. This is true especially for link qualities, that in the emulator are fixed, while in the real word are time varying. To overcome this problem, we have put the devices close one another to obtain perfect local link. Then we simulated different link qualities opportunely tuning the HOP_PENALTY parameters of intermediate nodes. In particular we setted an high HOP_PENALTY value of 100 at node B_2, that represent the back-off sub-optimal route. In this way, before failure of node B_1, the originator B_2 is never chosen by C and D as router toward node A and vice-versa. The real test-bed configuration is depicted in figure 5.7.

5.5.1 Standard B.A.T.M.A.N. convergence time

We have run the same experiment as in the emulated environment, using ICMP packets to monitor connectivity between node A and stations C, D. We have also used the same definition of convergence time, as defined in 5.2.

The obtained results reflect the emulation outcomes, confirming the slow B.A.T.M.A.N. convergence after a failure due to a temporary loop formation. Also the increase in convergence time variance using low HOP_PENALTY values is confirmed. In particular average convergence time, resulting from the real test-bed, are aligned with the average values obtained with the emulation. This

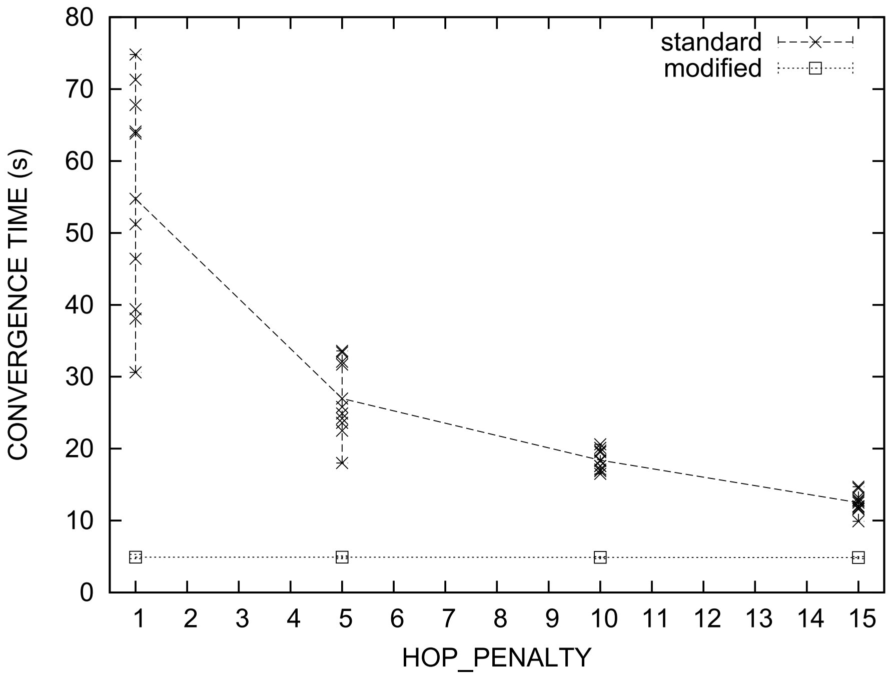


Figure 5.8: *Average convergence time in case of node failure varying the HOP_PENALTY measured in the real test-bed.*

confirms that the simulation using virtual machines is a good technique to evaluate routing protocols behaviour.

The only difference observed is the absence of connection instability observed in the emulated environment. This is probably due to the different network topology, in fact the problem of local OGM echoes erroneously processed as path OGMs, described in section 5.2, does not emerge because all existing direct links are also optimal paths.

5.5.2 Modified version convergence time

As for the standard B.A.T.M.A.N. implementation, real world tests confirm the results obtained in the emulated environment. Also the average convergence time and variance are similar.

The results confirm that proposed modification guarantees loop-freeness and, consequently, it assures bounded mean converge time [1]. We confirmed that the HOP_PENALTY parameter tuning does not influence in any case the convergence time, as the final user will expect. The convergence times measured in the real test-bed are reported in figure 5.8.

[1]Convergence time will depend only from MAX_SEQNO_GAP, ORIG_INTERVAL and OGM loss probability. It is not influenced by HOP_PENALITY and by routing misbehaviour.

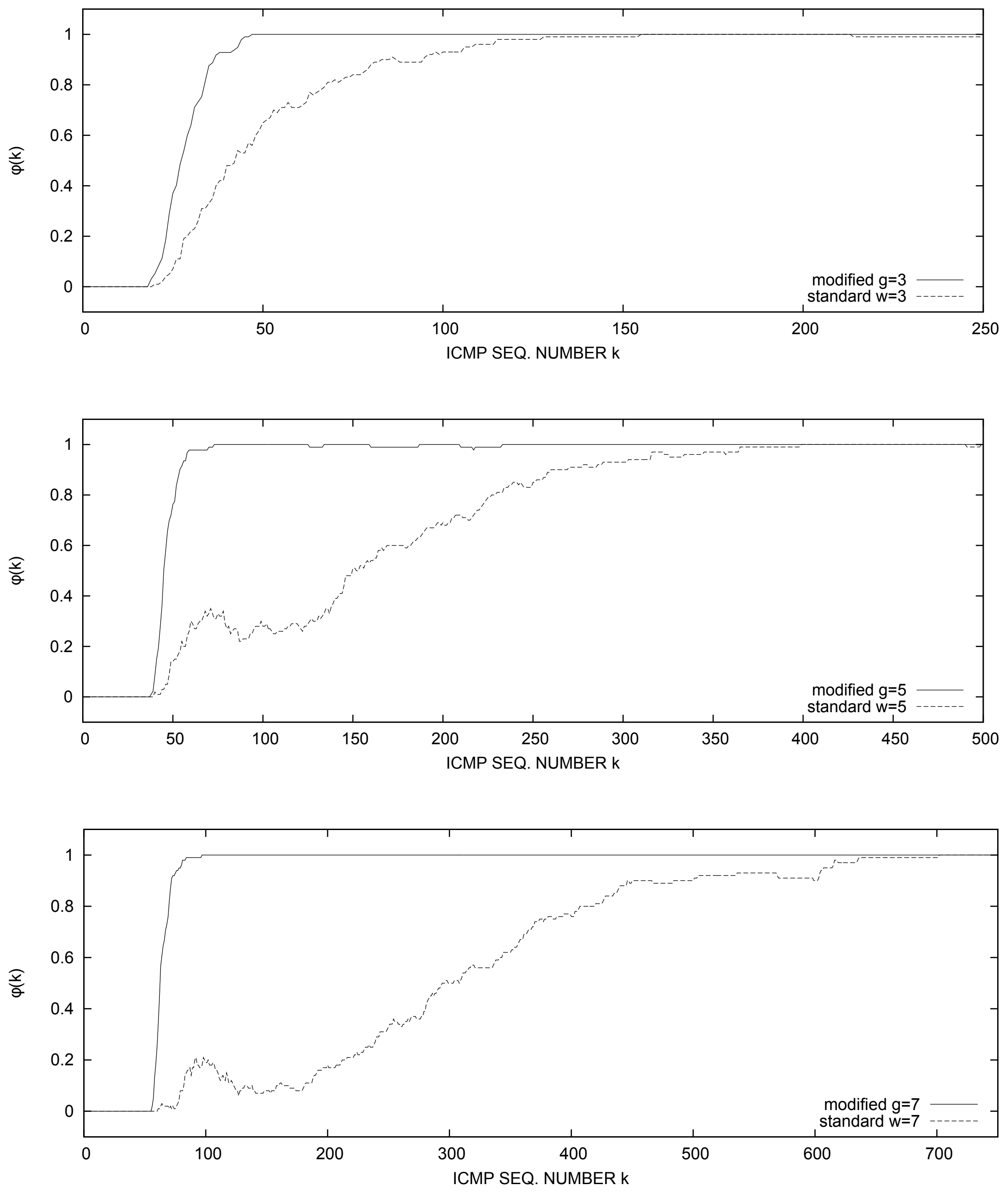


Figure 5.9: *Comparison between standard implementation and modified version with different values of TQ_GLOBAL_WINDOW_SIZE or MAX_SEQNO_GAP. Can be noticed that standard B.A.T.M.A.N. converges slowly due to a phase with non zero loss probability, caused by the formation of routing loops. The modified version, on the other hand, finds immediately a new stable route.*

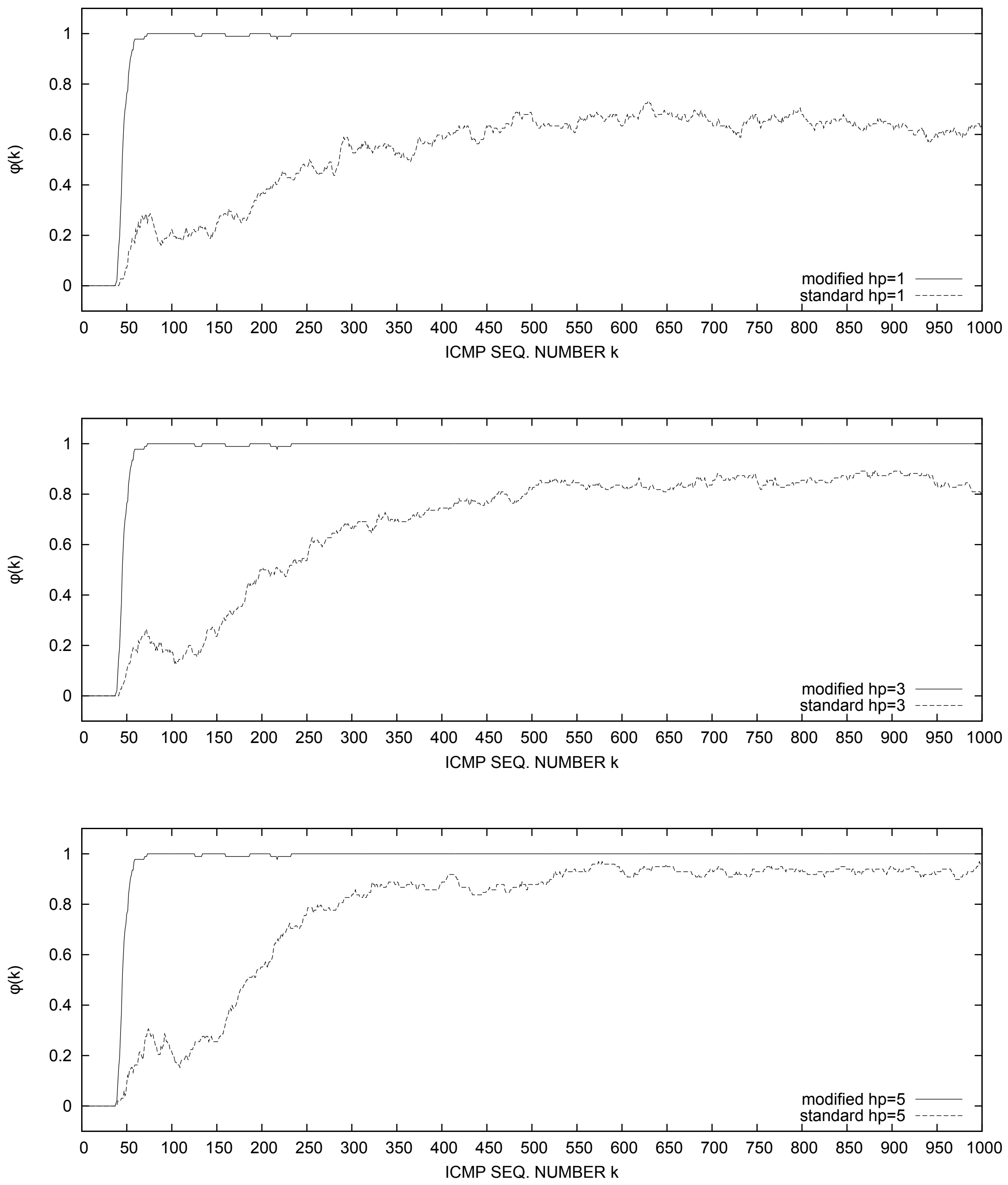


Figure 5.10: *Comparison between standard implementation and modified version with values of HOP_PENALTY less than the default value* 10. *Can be noticed that standard B.A.T.M.A.N. does not converges and remains in a situation with non zero loss probability. Stability of modified version, on the other hand, is not influenced by parameter setting.*

Chapter 6

Conclusion

In the thesis we have tackled the problem of routing in Wireless Mesh Network. We have focused our attention on the prominent B.A.T.M.A.N routing protocol, describing in details its working principles and reporting also the various features introduced in the latest versions.

We started providing a formalization of the Transmission Quality (TQ) routing metric employed in B.A.T.M.A.N., as till now a formal description was missing. Monotonicity and isotonicity of TQ metric have been demonstrated in an ideal loss free situation, deriving a proof of optimality, consistency and loop-freeness of the B.A.T.M.A.N. routing protocol in this ideal case.

Since B.A.T.M.A.N. routing information are sent in broadcast, we examined whether losses of routing management frames, that can be frequent in wireless networks, modify formal properties of the TQ metric. We evidenced that consistency and optimality cannot be obtained without assuring guaranteed delivery of routing management frames, so we concentrated our attention on loop freeness. We have demonstrated that even a single OGM loss can cause TQ monotonicity violation, possibly producing routing loops. We have built a sample scenario in which monotonicity violation causes routing loops, and then we have identified the factors causing this problem, which are path TQ averaging and a mechanism that we called *fast OGM forwarding.*

The routing loops formation is a major problem for a routing protocol, so a modification of OGM forwarding rules and path TQ calculation has been described. The modification allowed the formal demonstration of the metric monotonicity, deriving also a proof for loop freeness which is a fundamental characteristic of a routing protocol.

To confirm our analysis, we have conducted a number of experiments in an emulated, controlled scenario, where single node failures allow the repeatable measure of the performance difference between the two protocol versions. We have shown that the standard implementation convergence time is heavily influenced by routing loops formation and depends also from TQ_GLOBAL_WINDOW_SIZE and HOP_PENALTY parameters. In particular when setting little value of HOP_PENALTY, the protocol exhibits intermittent connectivity that destroys the performance.

On the other hand, we have confirmed that our modification is actually immune from routing loops, and its convergence time is bounded. In particular opportunely tuning MAX_SEQNO_GAP and ORIG_INTERVAL we can balance between a fast reactive protocol and a more stable one, depending on the network characteristics. The results obtained in the emulated environment have been also confirmed running the same experiment in a real test-bed.

In a future work, it would be interesting to test the behaviour of B.A.T.M.A.N. in networks with mobile nodes. During this work we have collected sufficient clue to say that, in a similar scenario, standard version can become unstable, causing the formation of routing loops. The modified version, on the other hand, is immune from loops so it would exhibit much better performance.

Appendix A

Mesh network emulation

For our emulation, we decided to use virtual machines running unmodified version of the B.A.T.M.A.N. protocol. This approach has the advantage of not introducing errors coming from translation of the protocol into specific network simulators such as NS-2.

As far as we know does not exist any network emulator capable to simulate wireless links. So we decided to use a modification of the well known network emulator *VDE switch*, to connect various protocol instances running on *qemu* virtual machines. The *wirefilter* package has also been used to modify packet loss probability and network delay. These tools are all parts of the *VDE (Virtual Distributed Ethernet)* project [1].

This configuration works well for our objective of testing the convergence time of the protocol, and in general it is suitable to analyse B.A.T.M.A.N. behaviour in different network topologies and situations. On the other hand, a similar approach cannot be used to estimate other protocol performance metrics, such as throughput or delay. In fact, in the emulated test-bed all links are full duplex, and there isn't a simple way to simulate wireless links characteristics such as bit-rate adaptation, retransmissions, inter and intra flow interferences, etc.

A.1 VDE

VDE (Virtual Distributed Ethernet) is a powerful tool that allow to create an Ethernet compliant virtual network, that can connect different types of hosts. In our case, we connect virtual machines all executed on the same hosts, and this give us the possibility to create whatever topology we want.

[1]http://vde.sourceforge.net/

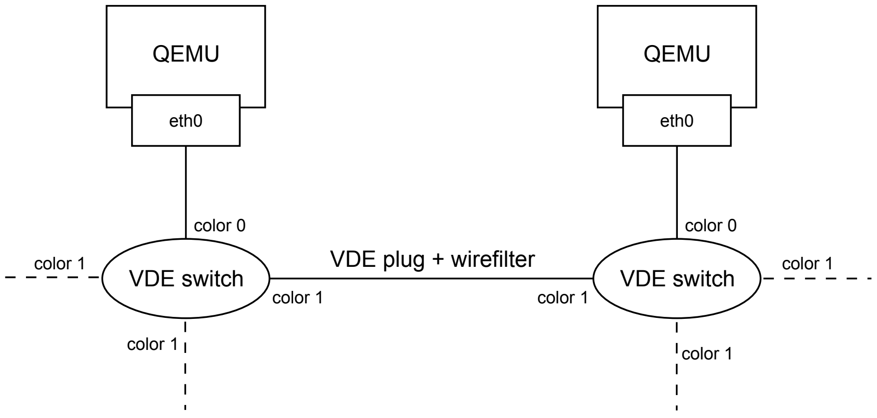


Figure A.1: *Illustration of VDE configuration. VDE switch only forwards data to ports with the same color thus allowing only direct neighbour communication.*

VDE offers tools to create the virtual counterpart of real network stuff, such as switches and cables to interconnect the hosts. We will see that these tools cannot be used directly in our case, but they need little adjustments to better simulate a WMN.

A.1.1 VDE switch

VDE switch is the tool used to connect VDE hosts, or better VDE plug attached to hosts. We cannot use directly VDE, because we do not want to create a unique broadcast domain, but instead we want only neighbour nodes communicating directly. In this way we enforce multi-hop communication, so B.A.T.M.A.N. protocol can work properly.

The patch used to modify the standard VDE switch assign to each VDE switch port a number (or color). The communication is allowed only if colors of ports are different. In this way only one-hop neighbours can communicate directly. The figure A.1 illustrates the concept.

A.1.2 VDE plug and wirefilter

A VDE plug is essentially a virtual cable used to connect different VDE switches. To simulate network conditions such as packet loss, bandwidth or delay, the wirefilter tool has been used. Wirefilter acts on packet traversing the virtual cable, according to parameters provided independently from packet type.

A modification of wirefilter has been used to differentiate between different packet type. In particular it is important to differentiate between broadcast packets, that can get lost, and unicast packets that has substantially guaranteed delivery, thanks to physical acknowledgements.

A.2 Qemu and OpenWrt

Qemu is an open source processor emulator that allow to emulate a number of different system architectures. For our test we have used x86 machines running an OpenWrt operating system. This choice is due the diffusion of this operating systems in the world of access points and embedded devices, especially in low cost network devices and in open community developing free wireless mesh network for internet access [2]. There already exist also commercial solutions for WMN based on device running OpenWrt operating system, together with B.A.T.M.A.N. [3].

Interfaces of emulated machines are created using the vde back-end in order to interconnect the machines using VDE switches as described above. For each machine also a tap interface has been created to communicate directly with the host machine, allowing to monitor and log the traffic on each machine network interface.

A.3 B.A.T.M.A.N.

The B.A.T.M.A.N. module is natively available for OpenWrt. It can be chosen between the development version and the latest stable version. For our tests we used stable version 2011.3.1. The modified version has been also implemented starting from this release source code.

The B.A.T.M.A.N. module has been added to Openwrt at compile time, but can also be added at run-time using the ipkg utility.

[2]See for example http://start.freifunk.net/, http://villagetelco.org/ and http://wiki.ninux.org/

[3]http://www.open-mesh.com/

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