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Inter-flow and intra-flow interference mitigation routing in wireless mesh networks

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A B S T R A C T

In this paper, we address the problem of QoS support in an heterogeneous single-radio single-channel multi-rate wireless mesh network. We propose a new routing metric that provides information about link quality, based on PHY and MAC characteristics, including the link availability, the loss rate and the available bandwidth. This metric allows to apprehend inter-flow interferences and avoid bottleneck formation by balancing traffic load on the links. Based on the conflict graph model and calculation of maximal cliques, we define a method to estimate the available bandwidth of a path which considers, in addition, intra-flow interferences. Finally, we propose a routing protocol that supports this metric and we study by simulation its performances compared to different existing routing metrics and protocols. The results revealed the ability of our protocol (LARM) to support the network scalability as well as its ability to choose routes with high throughput and limited delay.

Keywords:

QoS

Routing

Available bandwidth

Interference

Conflict graph

1. Introduction

Wireless Mesh Networks (WMNs) are a flexible, quickly deployable wireless networking solution that takes advantage from the absence of a rigid infrastructure. These networks are used to provide rural areas, where broadband infrastructure is not available, with a reliable Internet access based on multi-hop connections [1].

To support next-generation applications with real-time requirements, WMNs must provide improved Quality of Service (QoS) guarantees [2,3].

The problem of interconnecting the multi-hop wireless network to the backbone requires QoS guarantee not only over a single hop, but also over an entire wireless multi-hop path. Subsequently, the QoS parameters need to be propagated within the whole network, in order to extend reliability and high performance conditions.

Moreover, routing is considered as a key issue of QoS support over wireless multi-hop networks, since it determines whether the coming data traffic can be served on a high quality path or not.

On the other hand, in a WMN, a node transmits its data via a shared wireless channel, which has inherent broadcast and lossy

characteristics. Data transmissions over this wireless channel are constrained by interference and limited bandwidth resources [4].

Besides the interference coming from the physical environment, a coming data traffic may interfere with two types of traffics, 1) neighboring traffic including the traffic cross the same node and adjacent nodes, commonly called inter-flow interference, 2) this data traffic itself (we call it self-traffic) along the path, commonly called intra-flow interference. To ensure accurate path quality estimation, both these two types of interference should be considered [4].

However, estimating interference in a wireless network and circumventing its effects is not a trivial task since the amount of interference depends on many factors including the radio propagation environment, spatial node distribution and MAC protocol dynamics. Therefore, adding interference-awareness to the routing protocol decisions is crucial.

Identifying paths with maximum available bandwidth is, also, one of the main issues concerning QoS in WMNs. The available path bandwidth is commonly defined as the maximum additional rate a flow can push before saturating its path [5]. As communications in WMNs are multi-hop, the bandwidth consumed by data flows and the available resources to a node are not local concepts, but are related to the neighboring nodes in carrier-sensing range [6]. Hence, the challenge introduced here is how to estimate the available bandwidth for an incoming data flow on the entire path without violating the bandwidth guarantees of existing flows and

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with the only knowledge of the residual channel resources of each link. Then, estimating the widest path when accounting for intra-flow and inter-flow interferences remain a major challenge for interference aware routing.

This paper focuses on the problem of identifying the maximum available bandwidth path from a source to a destination, which is also called the Maximum Bandwidth Problem (MBP)[7]. We propose a new routing metric that captures the concept of link availability based on the PHY and MAC parameters, such as the loss rate, the available bandwidth, etc. We use the conflict graph model and calculation of maximal cliques to estimate the available bandwidth of a path when accounting for intra-flow interference. Finally, we propose a routing protocol that supports this metric and we study its performance by simulation compared to different existing routing metrics and protocols in the literature. Results showed that our proposal supports the network scalability and is well able to choose routes with high throughput and limited delay, thus, better delivery of data traffic.

The rest of this paper is organized as follows: After presenting an overview of the related works in Section 2, we explain the design of our residual link capacity based routing metric with interference consideration in Section 3. Section 4 describes our routing protocol in details, and Section 5 presents our extensive simulation results. We finally conclude our paper in Section 6.

2. Related works

In the context of mesh networks, QoS guarantees are typically provided for bandwidth and/or end-to-end delay. The problem of QoS is important for these networks since they are typically used for providing broadband wireless Internet access to a large number of distributed users and networks. QoS support in multihop wireless networks has been studied extensively in literature and it has been addressed from a number of aspects. A large number of QoS solutions provide QoS by integrating wireless link quality metrics. New metrics, such as ETX [8], ETT [9], WCETT [9], etc. [10], are proposed towards a quality-aware routing, in order to more reflect the variations of link quality caused by transmission capacity, loss probability, interferences, etc. ETX represents the number of times a node expects to transmit and retransmit a packet for a successful delivery. ETT is an improved version of ETX where the ETT of a link is defined as the expected MAC layer duration for a successful transmission of a packet. By accounting for both the link capacity and quality of a link, this metric offers a better estimation and ensures both reliability and efficiency. Weighted Cumulative Expected Transmission Time (WCETT) is the first multi-channel metric for mesh networks. It is determined by the amount of time used by a frame to attend a destination and the maximum time period consumed on links sharing the same channel. The main motivation for WCETT was to specifically reduce intra-flow interference by minimizing the number of nodes on the same channel in the end-to-end path.

Among these metrics, some improvements of ETX, such as ETT metric, only consider the total capacity of a wireless link and do not account for possible degradation of the bandwidth due to interferences or parallel data transmissions [11]. Some other proposals only treat the intraflow or the interflow interferences but not both at the same time. We have made, in a previous work [12], an experimental performance study of some of the proposed metrics and based on the results found we propose, in this work, new routing metrics specifically designed for wireless mesh networks.

From another perspective, a significant number of QoS solutions for wireless multi-hop networks provide QoS guarantees by integrating routing with resource reservation. Authors in [13] propose a Contention-aware Admission Control Protocol (CACP) which is an admission control algorithm for single-channel multi-hop networks

based on the knowledge of local resources available at a node and the effect of admitting a new flow on the neighborhood nodes. Based on the carrier sensing mechanism at the MAC layer, they estimate the local available bandwidth at a node. The performance evaluation of CACP was made associated to DSR, but it is generic enough to work with almost any existing on-demand routing protocol for ad hoc networks. Similar solutions have been proposed [14–16] in which the available bandwidth at a node is considered as the minimum bandwidth within a two-hop neighborhood of that node. Here also the route discovery process is coupled with admission control.

In another solution [17], authors propose two new mechanisms for available bandwidth estimation at a node. The first mechanism increases the carrier-sensing range so that flows which are near the boundary of the latter can also be taken into account. However increasing the carrier sensing range is not supported by current hardware as vendors do not allow low level access to the wireless firmware. In the second mechanism, they used the classical concept of packet probes and estimated available bandwidth using probe dispersion observed based on mathematical models. The authors of [17] integrate bandwidth estimation and admission control with the on-demand LUNAR routing protocol. MARIA : Mesh Admission control and QoS Routing with Interference Awareness [18] is another solution. With MARIA, a local conflict graph is computed at each node and an admission control is performed. Nodes, then, exchange their flow information periodically and compute their available residual bandwidth based on the local maximal clique constraints. Admission decision is made based on the residual bandwidth at each node. Authors also propose an on-demand routing protocol which incorporates the admission control during the Route Discovery phase.

Some of the discussed existing QoS routing protocols operate with the knowledge of the available bandwidth of each link [19,20]. In these works, the available bandwidth of a path is computed, generally, based on the available bandwidth of each link on this path. Liu and Liao [21] gave a new link metric which is the available bandwidth of the link divided by the number of its interfering links. The path bandwidth is thus defined as the minimum value of the weights of all its composing links. In the mechanism described in [22], the available bandwidth of a path is the minimum bandwidth among the links on the path divided by the number of hops on the path. Such formula is not able to reflect the exact path bandwidth. Authors in [23] propose a protocol that checks the local available bandwidth of each node to determine whether it can satisfy the bandwidth requirement of a new data flow. Some works [24–26] consider the TDMA-based MAC model and focus on how to assign the available time slots on each link for a new flow in order to satisfy the bandwidth requirement of the new flow.

The algorithm suggested in [31,33] is used to generate conflict graphs independently of the underlying interference model. Authors used the notion of radio co-location interference, which is caused and experienced by spatially co-located radios in multi-radio multichannel (MRMC) WMNs. They experimentally validate the concept, and propose a new all-encompassing algorithm to create a radio co-location aware conflict graph. This novel conflict graph generation algorithm is demonstrated to be significantly superior and more efficient than the conventional approach, through theoretical interference estimates and comprehensive experiments. The results of an extensive set of simulations run on the IEEE 802.11g platform strongly indicate that the radio co-location aware conflict graphs are a marked improvement over their conventional counterparts.

Authors in [34] propose an interference-aware channel assignment algorithm and protocol for multi-radio wireless mesh networks that address overlapping channel assignments. The proposed solution utilizes a novel interference estimation technique imple-

mented at each mesh router to minimize interference within the mesh network and between the mesh network and co-located wireless networks. An extension to the conflict graph model, the multi-radio conflict graph, is used to model the interference between the routers. They demonstrate their solutions practicality through the evaluation of a prototype implementation in a IEEE 802.11 testbed and they carried out an extensive evaluation via simulations.

These proposals of available bandwidth calculation cannot be solved in polynomial-time. Even though we can find the available bandwidth of a given path, it is not easy to identify a schedule that achieves that bandwidth since the scheduling problem is also NP-complete [26].

Furthermore, most of these works consider the total offered link capacity and don't account for possible inter-flow interferences which is the main cause of link bandwidth degradation. In addition, in multi-hop WMNs, the consumed and the available resources to a data flow are not local concepts, but are related to the neighboring nodes in the end to end path. Then, we need a complete routing solution that gives accurate estimation of available bandwidth along a given path.

Our main goal is to develop a practical routing protocol that allows packets to go through the estimated widest path. This widest path is identified when considering both intra-flow and inter-flow interferences.

3. Residual link capacity based routing metric with interference consideration

The objective of any QoS solution is to provide applications with guarantees in terms of bandwidth, delay and jitter. Providing these guarantees in a distributed and wireless environment generally requires a clear estimation of available resources vis-a-vis individual requirements of each node, data flow or application. This knowledge is therefore crucial for any communication on a shared channel in the wireless network.

Since it is difficult to completely separate in time and frequency simultaneous transmissions in wireless networks, some transmissions will be produced at the same time and in the same frequency band. These simultaneous transmissions may, depending on the network topology, interfere and degrade network performances.

Most of the existing routing metrics in the literature consider only the total capacity of a wireless link and do not take into account the possible degradation of bandwidth due to interference or simultaneous data transmissions. Moreover, there are few proposals which address the problem of both intra-flow and inter-flow interference at once. We conducted, in a previous work [11,12], an experimental performance study of some of the existing metrics and based on its results we propose, in this work, a new routing metric specifically designed for wireless mesh networks. This metric aims to accurately measure the available capacity of a link when taking into account both the current use of the link and possible interferences with neighboring links. In fact, inter-flow interference occurs when different flows are being transmitted at the same time and then sharing the same available resource. In other words, the interflow interference affects the amount of residual channel resources on each link that will be allocated for a new flow [27].

We propose in the following, the study of a scenario to highlight this phenomenon.

In this simulation we consider six nodes configured as shown in Fig. 1(a). The radio transmission range is set at 250 m and the interference zone is 550 m. Node A is out of the transmission range of node C, but in its interference zone. The node E is in the transmission zone of the node A and is out of the interference range of the node C. Three CBR traffic flows of 2 Mbps are established be-

tween the nodes A and B, the nodes E and F and the nodes C and D. Transmissions are spaced by a period of 10 s. The links have different capacities, as shown in Fig. 1(b).

As shown in Fig. 1(b), after the transmission of flows 1 and 2, node C is still able to admit flow 3. However, since node A is in the interference zone of node C, flow 3 is capable of consuming the residual capacity of A which is, in fact, insufficient. In other words, even if the local bandwidth permits, node C does not have enough neighboring bandwidth (which is, the bandwidth available on the other links in the path) for flow 3.

To overcome the impact of inter-flow interference, we propose a first metric component called Residual Link Capacity based metric (RLC) given by the equation below:

$$RLC_l = B_l - \frac{Tx_l}{\omega} \quad (1)$$

Where B_l is the link bandwidth and Tx corresponds to the traffic occupying the link l in transmission and in reception during the time window ω . The routing protocol selects the link with the greater RLC. A route's RLC corresponds then to the minimum of RLCs of links composing the route.

$$RLC_{route} = \min(RLC_l)_{l \in route} \quad (2)$$

Using this metric, each link is initialized to its bandwidth so that the routing protocol can choose from the start the route offering the greater bandwidth and thus supporting the greater traffic. Since it is based on real exchange of data in the network, the RLC based metric gives a real estimation and thus allows a more efficient routing. This routing metric is load sensitive i.e. the route decision changes when there are links with larger residual bandwidth which are more convenient to support larger data traffic.

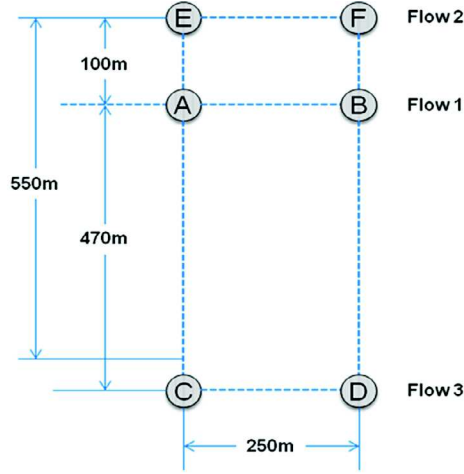
This metric is improved to consider intra-flow interference. Intra-flow interference occurs when a data packet is being transmitted over multiple links along a path. In order to avoid conflict at the receiving node, some links may remain idle. We describe here after the interference model adopted in this work and the bandwidth estimation of each link. Our new metric Residual Link Capacity Based Routing Metric with Interference consideration (RLCI) is designed based on this information.

3.1. Preliminaries

In this section, we give an overview of the clique-based method for computing the available path bandwidth.

In wired networks, nodes are able to know the amount of available resources in the medium and how much bandwidth is being used. However, in wireless networks, where the medium is shared between multiple nodes, communication from one node may affect the bandwidth of neighboring nodes. Therefore, neighboring nodes should cooperate in a distributed manner to correctly identify the available resources which are no longer local concepts. Generally, we distinguish two types of interferences: intra-flow interferences and inter-flow interferences.

To model the interference relationship between links, one common method is the use of interference conflict graph. This method is used in several existing works [28,29]. Given a wireless network, each link becomes a node in the conflict graph. If two links in the wireless network interfere with each other i.e. cannot be active simultaneously, we put an edge between the corresponding nodes in the conflict graph. The example depicted in Fig. 2 illustrates the interference modeling using conflict graph. The wireless network based on a six-link chain topology is given in Fig. 2(a) and the corresponding conflict graph is given in Fig. 2(b). Assuming that all nodes have the same transmission or communication range R_c and the same interference or sensing range R_s as represented, we conclude that link 1 and 2, for example, conflict with each other



Node	Link	Local Available Bandwidth (Mbps)
A	AB	5
E	EF	15
C	CD	10

Flow 1 starts

Node	Link	Local Available Bandwidth (Mbps)
A	AB	3
E	EF	13
C	CD	8

Flow 2 starts

Node	Link	Local Available Bandwidth (Mbps)
A	AB	1
E	EF	11
C	CD	8

Flow 3 starts

Node	Link	Local Available Bandwidth (Mbps)
A	AB	Congested
E	EF	11
C	CD	6

Fig. 1. Inter-flow interference : (a) Simulation topology; (b) Residual link capacity variations.

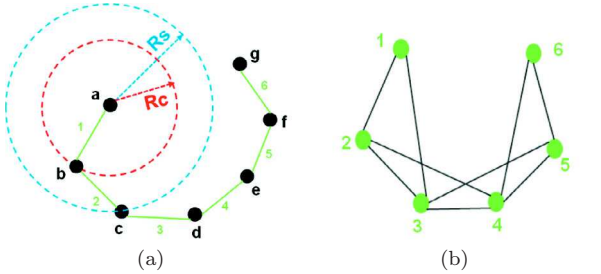


Fig. 2. Illustration for interference model. (a) The original graph, (b) The conflict graph.

because node b cannot transmit and receive at the same time. Link 1 and 3 are also conflicting because node c 's transmission will introduce enough interference for the reception at node b .

An *interference clique* in the wireless network is a set of vertices that mutually conflict with each other. In the conflict graph, the corresponding nodes of these links form a complete subgraph.

A *maximal interference clique* is a complete subgraph that is not contained in any other complete subgraph. For example, 1, 2, 3 and 3, 4, 5 are maximal cliques while 1, 2 and 1, 3 are not maximal cliques.

Relying on this clique-based formulation, we describe below the method to capture bandwidth sharing among links within the path. Given a wireless network, we denote $\{Q_1; \dots; Q_k\}$ as the maximal interference clique set of the network, C_q as the capacity of a clique q , $B(l)$ as the total bandwidth of link l and $B(p)$ as the estimation of the available bandwidth of path p . Then, considering a

path $p = \langle l_1, l_2, \dots, l_h \rangle$, the available bandwidth of the path p is estimated as follows [27]:

$$B(p) = \min_{q \in Q_p} C_q; C_q = \frac{1}{\sum_{l \in q} (\frac{1}{B(l)})} \quad (3)$$

The rationale behind the formula is: transmissions on the links in a clique cannot be concurrent but occur in a serial manner. Thus, $\sum (\frac{1}{B(l)})$ represents the time it takes for 1 Mbit data to traverse all the links in the clique q . C_q is thus the bandwidth available over the clique q . The available bandwidth of the path is the bandwidth of the bottleneck clique.

Let's illustrate the example in Fig. 2(a): Consider the path $p = \langle a; b; c; d; e; f \rangle$. Let $B(1)$, $B(2)$, $B(3)$, $B(4)$ and $B(5)$ of the network in Fig. 2(a) be 10, 50, 25, 20 and 5 Mbps, respectively.

There are two maximal cliques on this path which are $\{1, 2, 3\}$ and $\{3, 4, 5\}$.

$$C_{\{1,2,3\}} = \frac{1}{\frac{1}{10} + \frac{1}{50} + \frac{1}{25}} = \frac{50}{8} = 6.25 \text{ Mbps}$$

And :

$$C_{\{3,4,5\}} = \frac{1}{\frac{1}{25} + \frac{1}{20} + \frac{1}{5}} = \frac{100}{29} = 3.44 \text{ Mbps}$$

The estimated available bandwidth of path p is :

$$\min\{6.25, 3.44\} = 3.44 \text{ Mbps.}$$

However, the size of a maximal clique depends on how many links interfere with each other, which depends on the interference model adopted in the network. Due to the popularity of the 802.11 technology, we develop our work based on this MAC protocol. Both

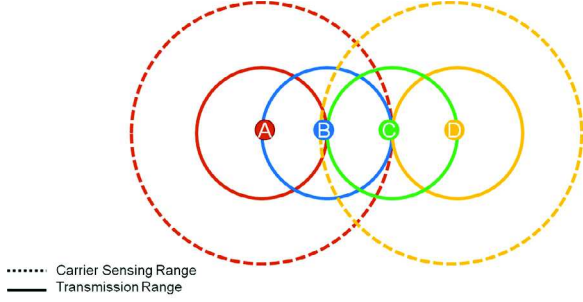


Fig. 3. TRCA interference model with $r=2$.

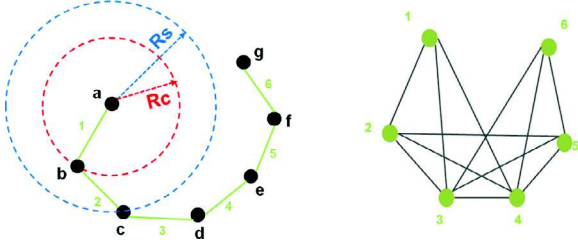


Fig. 4. Conflict graph under TRCA interference model (a) The original graph, (b) The conflict graph.

the two-way handshake DATA/ACK and the four-way handshake RTS/CTS/ DATA/ACK of 802.11 require the receiver of a data packet to send an ACK back to the sender of the data packet. Therefore, for a packet transmission to be successful, both the sender and the receiver should not be interfered by other nodes. a is interfered by another node b if a is within the interference range of b . In other words, the transmissions on links $(u; v)$ and $(s; d)$ are successful at the same time if and only if both s and d are outside the interference ranges of u and v . This model is referred as the bidirectional transmission model or *Transmitter-Receiver Conflict Avoidance (TRCA) interference model* and is adopted by many existing works [11].

We define the transmission range of a node to be one hop, while the interference range to be r hops and to simplify our discussion, we set $r = 2$ but our results can be extended to any value of r . Then, according to this assumption, the interference modeling of chained nodes would be as shown in the Fig. 3 below:

We also consider a single-radio single-channel configuration. We use the previous network in Fig. 3 to illustrate the TRCA interference model.

Based on the conflict graph in Fig. 2b assuming $r = 1$ which is not the TRCA interference model we are using in this paper, when node a sends data to node b , node c is not allowed to transmit since it is in the interference range of b . This means that links 1 and 3 interfere with each other. Then, each maximal clique contains three consecutive links.

Under TRCA model, when node a sends data to node b , node d is not allowed to transmit since it is in the interference range of b . This means that links 1 and 4 interfere with each other. Then, each maximal clique contains four consecutive links (cf. Fig. 4b).

Based on the TRCA interference model, since all maximal cliques in the conflict graph contain at least four interfering links, the formula for estimating the available bandwidth of a path p becomes as follows:

$$B(p) = \min_{1 \leq k \leq (h-4)} C_k;$$

$$C_k = \frac{1}{\frac{1}{B(k)} + \frac{1}{B(k+1)} + \frac{1}{B(k+2)} + \frac{1}{B(k+3)}} \quad (4)$$

Where $B(k)$ represents the available bandwidth of the link (l_k, l_{k+1}) . Further details about this clique-based estimation can be found in the following works [10]. According to the example in Fig. 1(a) and under TRCA interference model, the estimated path bandwidth of the path $p = \langle a, b, c, d, e, f \rangle$ is:

Where :

$$C_1 = \frac{1}{\frac{1}{10} + \frac{1}{50} + \frac{1}{25} + \frac{1}{20}} = 4.76 \text{ Mbps}$$

And

$$C_2 = \frac{1}{\frac{1}{50} + \frac{1}{25} + \frac{1}{20} + \frac{1}{5}} = 3.22 \text{ Mbps}$$

Then, $B(p) = \min\{4.76, 3.22\} = 3.22 \text{ Mbps}$.

3.2. Metric design

In this section, we introduce our novel metric based on residual link capacity and accounting for both intra-flow and inter-flow interferences. The purpose of this metric is to measure accurately the residual capacity of each link when considering the possible conflict with eventually other transmissions occurring at the same time. The routing decision, then, will be based on links offering the greatest capacity, in other words, on widest paths. To avoid inter-flow interferences, we used the Residual Link Capacity (RLC) metric defined previously. This metric measures accurately the available bandwidth over a link since it captures the amount of data of all flows crossing the specified link. We apply, then, the clique based bandwidth estimation in order to consider possible intra-flow interferences. To model the interferences, we used the TRCA interference model described previously. This formulation guarantees a global and unique view inside the network i.e. that every node in the network will be aware of the widest neighboring links able to support additional traffic.

Each node first computes the residual capacity of its links. Then, for each path from this node to a destination node, it computes the available bandwidth over this path using the clique based formula introduced previously. We detail in Section 4 the routing protocol used to get information needed for the available path bandwidth calculation.

Given a wireless network, we denote $\{Q_1; \dots; Q_k\}$ as the maximal interference clique set of the network, C_q as the capacity of a clique q , RLC_l as the Residual Link Capacity of link l and $AB(p)$ as the estimation of the available bandwidth of path p . For each link l , RLC_l is estimated as follows:

$$RLC_l = TB_l - \frac{Tx_l}{\omega} \quad (5)$$

Where, TB_l corresponds to the total available bandwidth of link l and Tx_l corresponds to the amount of data occupying the link l during the time window ω .

Then, considering a path $p = \langle l_1, l_2, \dots, l_h \rangle$, the available bandwidth of the path p is no longer the minimum of RLCs of links composing the path but it is estimated as follows [27]:

$$AB(p) = \min_{1 \leq k \leq (h-4)} C_k;$$

$$C_k = \left(\frac{1}{RLC_k} + \frac{1}{RLC_{k+1}} + \frac{1}{RLC_{k+2}} + \frac{1}{RLC_{k+3}} \right)^{-1} \quad (6)$$

Hence, each node knows the residual capacity of neighboring links and is able to measure the widest path to a destination node while considering all possible interfering transmissions.

The main advantage of our routing metric RLCI consists of its consideration for both intra-flow and inter-flow interference. However, this metric is not isotonic and addresses the problem of local vision of available resources. We define the isotonicity property as introduced in [27]:

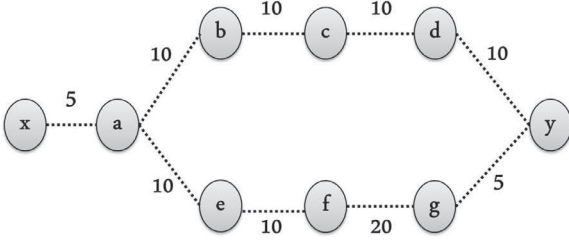


Fig. 5. Problem of local vision in the *widest path* estimation.

Definition. Left-isotonicity : The quadruplet $(S; \oplus; \omega; \geq)$ is left-isotonic if $\omega(a) \geq \omega(b)$ implies $\omega(c \oplus a) \geq \omega(c \oplus b)$, for all $a; b; c \in S$, where S is a set of paths, \oplus is the path concatenation operation, ω is a function which maps a path to a weight, and \geq is the order relation.

To illustrate this problem, we consider the example of the network in Fig. 5 where numbers on the links indicate the available link capacities in Mbits/s, the widest path from node a to node y is " a, b, c, d, y " because the path " a, e, f, g, y " presents a bottleneck (g, y) limited to 5 Mbits/s. However, from node x to node y , the widest path is instead " x, a, e, f, g, y " because it comprises the link (f, g) offering greater capacity.

According to our metric RLCI, the calculation of the available bandwidths on each path of this case study is given in the following equations :

$$AB(a, b, c, d, y) = \left(\frac{1}{10} + \frac{1}{10} + \frac{1}{10} + \frac{1}{10} \right)^{-1} = 2.5 \text{Mbits/s} \quad (7)$$

$$AB(a, e, f, g, y) = \left(\frac{1}{10} + \frac{1}{10} + \frac{1}{20} + \frac{1}{5} \right)^{-1} = 2.22 \text{Mbits/s} \quad (8)$$

$$AB(x, a, b, c, d, y) = \left(\frac{1}{5} + \frac{1}{10} + \frac{1}{10} + \frac{1}{10} \right)^{-1} = 2 \text{Mbits/s} \quad (9)$$

$$AB(x, a, e, f, g, y) = \left(\frac{1}{5} + \frac{1}{10} + \frac{1}{10} + \frac{1}{20} \right)^{-1} = 2.22 \text{Mbits/s} \quad (10)$$

In this case, a suitable routing mechanism is needed to unify the vision of all network nodes.

The study of this performance metric requires integration into a routing protocol adapted to compensate for its non-isotonicity. The protocol specification and evaluation of performance will be detailed in the next section.

4. Link Availability based Routing Mechanism (LARM)

4.1. Design considerations and path selection

We studied in a previous work [32] through simulations the impact of PHY/MAC protocols on higher layers. This study has not been done to announce or promote one particular routing protocol as the "winner" protocol having the best performance but it is done to check the conditions where each of the proposed protocols achieves the highest efficiency.

Results have revealed a notable superiority in the general performance of proactive routing protocols when used with IEEE 802.11n based MAC layer, particularly when the network get denser.

Reactive routing protocols are better fitting high stability networks. They are not very suitable for mesh networks because of the delays required to establish a valid route for each data sending. In fact, even if mesh nodes are static, links between nodes evolve and their characteristics change permanently.

On the proactive side, OLSR, cannot meet the non-isotonicity of our metric because of the use of MPR sets which restrict vision to two hops and thus give a partial view of the network.

Hence, to capture accurately the variability of links throughput, we adopt a proactive routing protocol that we called Link Availability based Routing Mechanism - LARM. This protocol is based on Destination Sequenced Distance Vector (DSDV) routing protocol with a number of improvements that we can summarize in the following points:

- Explicit detection of neighbors with link quality computation,
- Flexibility and dynamic routing decision adaptability with RLCI routing metric,
- Triggered and aperiodic updates of routing table instead of periodic updates,
- selection, according to an estimation of the offered bandwidth, a set of candidate paths to be diffused as best paths for neighboring nodes,
- Updates controlled by a threshold between the old value of the routing metric and the new value in order to ensure stability of the routes and minimize routing overhead.

Moreover, since our routing metric RLCI is essentially based on the residual capacity of the first four hops to a destination node, we propose that each source node includes this portion of the route in the data packet.

Our protocol, as described, can lead to significant routing overhead which can degrade network performances especially when it gets denser. For that reason, we propose some solutions to reduce and optimize this overhead in terms of number and size of control messages.

1. The dissemination of new routing information is performed when needed and not periodically in order to avoid overloading the network by control messages containing unchanged or relatively stable information. In other words, a node broadcasts a new path to a destination only when the residual capacities of links forming the path have undergone considerable changes which could, then, change the routing decision. The estimation of this change and its importance is set according to a threshold value that we describe in detail later.
2. The threshold value of the RLC of a link is important because it influences, firstly, the knowledge of link state and secondly the overhead induced by updates. A frequent update of this metric allows adaptability of the routing decision and makes it able to react quickly and effectively to network scalability in terms of topology and load. However, a frequent update of this metric can lead to network overload by control messages. We propose a threshold value proportional to data traffic through a link and total capacity of the given link in order to estimate the link occupation and its availability when neglecting the RLC variations due to control messages exchange.
3. To avoid disseminate all possible paths to a given destination, we select only k potential candidate paths as best paths for neighbor nodes based on the available bandwidth on each path. This eliminates paths with very low throughput, reduces the size of control messages which better adapts our solution for scalability.
4. Since the calculation of the metric RLCI is essentially based on the residual capacity of the first four hops only, we suggest that each node broadcasts for each destination the four next hops from itself and their respective residual capacities. This reduces the generated overhead.

Table 1
Topology information base format.

Dest.	Path	Next hop	Second next hop	Third next hop	Fourth next hop	AB(p)	Timer	Best path
D	P_1	n_1 $RLC(s, n_1)$	n_2 $RLC(n_1, n_2)$	n_3 $RLC(n_2, n_3)$	n_4 $RLC(n_3, n_4)$	$AB(p_1)$	$T(p_1)$	0/1
	P_2	m_1 $RLC(s, m_1)$	m_2 $RLC(m_1, m_2)$	m_3 $RLC(m_2, m_3)$	m_4 $RLC(m_3, m_4)$	$AB(p_2)$	$T(p_2)$	0/1

4.2. Routing information update

Below, we detail of our routing mechanism. We give, first, an overview of the routing information message which should be disseminated in the network in order to ensure reliable path selection. Afterward, we present the topology information database used to store routing information about all destination nodes in the network. We then describe, our packet forwarding mechanism which satisfies the consistency requirement. We apply Eq. (6) to estimate the available bandwidth of a path. To simplify our discussion, in the rest of our paper, we use available bandwidth instead of estimated available bandwidth when the context is clear. On the other hand, widest path refers to the path that has the maximum estimated available bandwidth.

First, all the nodes in the network exchange periodically HELLO messages to announce their neighborhood and to diffuse information about the amount of transmitted data during a time window ω on each link with symmetry consideration. Upon receipt of a HELLO message from a new neighbor, the node, using a cross-layer mechanism, calculates the residual capacity of the link connecting to it and insert a new entry in the routing table. When the neighbor originating the HELLO message is already known, we simply update the corresponding residual link capacity.

In the traditional distance-vector mechanism, a node only has to advertise the information of its own best path to its neighbors. Each neighbor can then identify its own best path. In Section 3, we mentioned that if a node only advertises the widest path from its own perspective, its neighbors may not be able to find the widest path.

In our routing protocol, if a node finds a new path or detects changes in the estimated available path bandwidth, it will advertise this path information to its neighbors using a Routing Information Vector (RIV). Given a path p from a source node s to a destination node d , node s advertises the tuple $(s, d, NH, RLC_{NH}, SNH, RLC_{SNH}, TNH, RLC_{TNH}, FNH, RLC_{FNH})$. NH , SNH , TNH and FNH are the next hop, the second next hop, the third next hop and the fourth next hop on p from s , respectively. RLC_{NH} , RLC_{SNH} , RLC_{TNH} and RLC_{FNH} are the corresponding residual link capacities. Based on the information contained in this Routing Information Vector, each node knows the link quality about the first four hops of the identified path and can calculate its available path bandwidth using Eq. (6).

4.3. Routing table

Each node maintains two tables: the traditional routing table used in DSDV and a topology information database where the node maintains all paths advertised by its neighbors or found by itself. In addition, for each path p , each node computes and maintains the available path bandwidth $AB(p)$ and a timer indicating the delay from the last update.

Finally, the node indicates with a Boolean value, if this path p is the widest path or not according to its own local vision. This widest path should be stored in the routing table too. The format of the topology information database is as follows (Table 1):

Based on DSDV, each routing entry is tagged with a sequence number which is originated by the destination, so that nodes can quickly distinguish stale routes from the new ones. Given two route entries from a source to a destination, the source always selects the one with the larger sequence number, which is newer, to be kept in the routing table.

After the network accepts a new flow or releases an existing connection, the local available bandwidth of each link will change, and thus the widest path from a source to a destination may evolve. In order to avoid frequent updates and network flooding with control messages, we define a $RLC_Threshold$ proportional to the total capacity of a link. When the change of the residual capacity of a link is larger than this threshold, the node will advertise the new information to its neighbors. After receiving the new bandwidth information, the available bandwidth of a path to a destination may be recalculated.

5. Performance evaluation

In this section, we conduct the simulation experiments under NS-3 [30] to investigate the performance of our routing protocol for finding the maximum available bandwidth path. We carried on simulations in two distinct parts: a first part dedicated to the performance evaluation of our metric RLCI compared to existing metrics such as Hop-Count (HC), ETX and ALM. The second part is carried out to evaluate our routing mechanism LARM in comparison with other existing protocols such as OLSR, DSR, DSDV and HWMP. This choice considers different routing strategies, diverse routing metrics and distinct PHY/MAC layers associated. For all performance scenarios, we consider a single-radio single-channel configuration.

5.1. Routing metric evaluation

The following simulations show how the estimation of the available path bandwidth calculated by our metric RLCI achieves a gain in throughput by identifying widest paths, ensuring, thus, better traffic fluidity. We considered a random network topology with 40 nodes sharing an area of $2500 \times 2500m^2$ (see Fig. 6). We chose a random distribution of the nodes in order to obtain different density levels. This allows us to study several interference scenarios which is our first objective. In other words, our approach can be validated or verified in the best and worst interference case scenario. Many works [35,36], however, have showed that strategic node placement in wireless mesh networks would give better network performances in terms of coverage, connectivity and fair mesh capacity.

We generated 12 TCP data flows with an average rate of 1 Mbits/s, i.e a traffic load of 30% of the total number of nodes. These data flows are transmitted at different times so as to have different estimations of the available bandwidth for each flow. The pairs of nodes in communication are selected according to the distance between them so as to have different route lengths. Fig. 7 represents, for each metric, the average throughput variation with the traffic charge injected in the network. The results show that the throughput decreases progressively with the traffic load. This

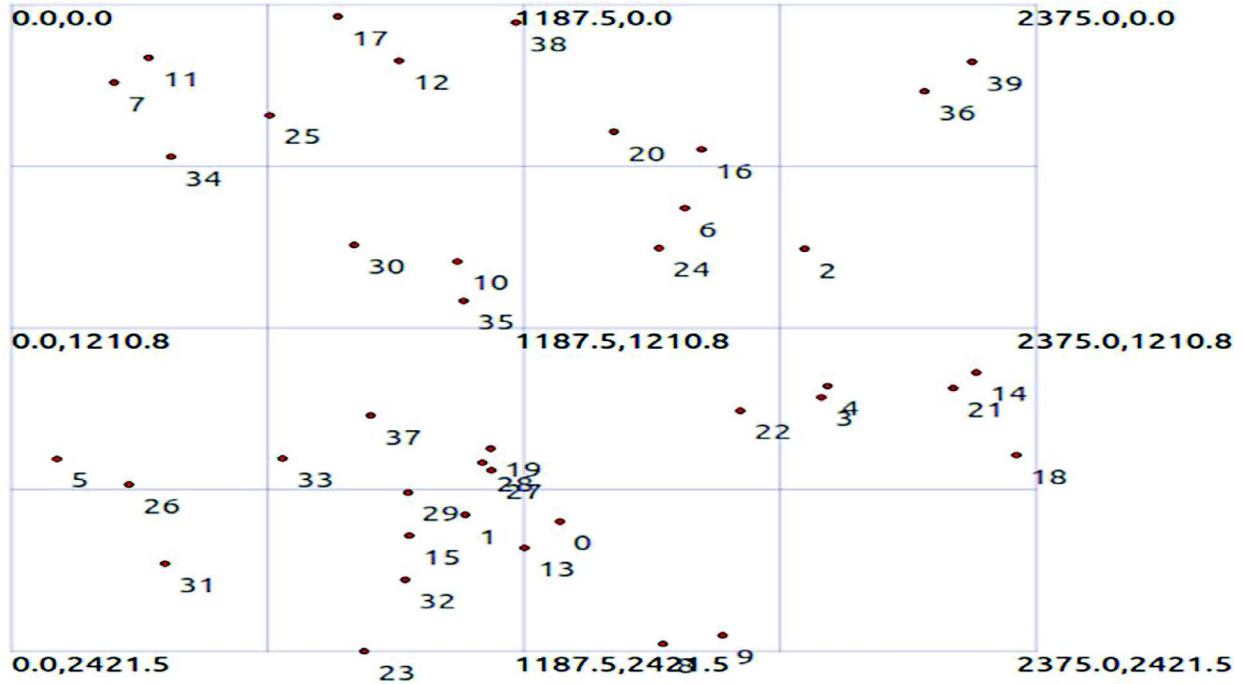


Fig. 6. Network Topology: 40 nodes distributed over a surface of $2500 \times 2500 \text{ m}^2$.

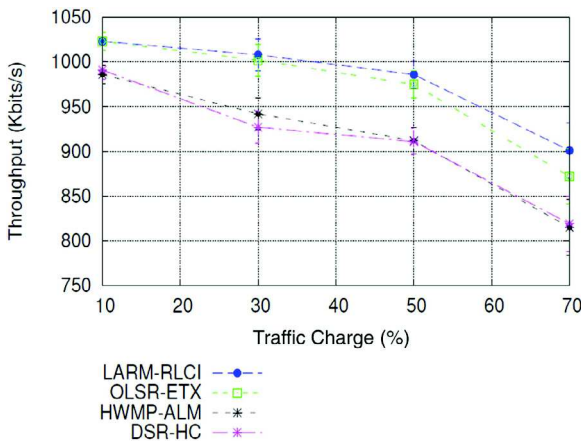


Fig. 7. Throughput evolution with the traffic charge.

decrease is due to data loss caused by possible collisions or saturated channel. Our metric RLCI incorporated in LARM protocol performs better than the other metrics with an important traffic load. Indeed, routing solutions based on shortest path quickly suffer from network congestion and do not propose adaptability strategy to such situation. With ETX, by measuring the loss rate on links, it enables the routing protocol to select paths with best delivery rates. However, as the loss rate estimation is based only on small probe messages and as it doesn't consider the impact of interference on data delivery, ETX may underestimate data loss and, then, do not guarantee optimal routing.

RLCI implements several performance criteria at once, allowing it to establish the best performance compromise and thus assess the best link quality. Compared to ETX and ALM, RLCI is based on residual link capacity which enables it to quickly adapt the routing decision into links offering more available bandwidth and then better appropriate to support more traffic. Furthermore, RLCI considers the impact of intra-flow and inter-flow interferences

which enables it to better fit situations of congestion or throughput degradation caused by neighborhood traffic.

To further detail the contribution of our metric RLCI, we represented in Fig. 8 the cumulative throughput per pair of nodes and this for different paths obtained with RLCI compared, respectively to, HC, ETX and ALM. Each data flow is represented by a point: the y-axis denotes the throughput values obtained for the metric RLCI, the x axis denotes the throughput obtained for the metric HC, ETX and ALM respectively. The function $y = x$ corresponds to the case where the two metrics select the same path or paths achieving the same throughput. The points above the line $y = x$ represents the data flow for which RLCI gives better performance as HC, ETX or ALM respectively. The results of the figure show better performance of RLCI compared to HC on most data flows. This is illustrated by the dense region above the line $y = x$. This region shows that routing based on the metric RLCI often finds paths with higher rates compared to HC based routing which is insensitive to link quality and traffic load.

Compared to ETX and ALM, the same observations are made. There are, however, some cases where ALM and ETX offer larger throughput than that obtained with RLCI. This statement is represented by the few points below the line $y = x$. However, the differences between the throughputs obtained are minimal in most cases. For example, a flow, providing a throughput equal to 512 Kbits/s with ETX, provides a throughput equal to about 460 Kbits/s with RLCI.

We randomly select 74 random multi-hop data flows and investigate the throughput of individual flow produced by the different routing metrics. Fig. 9 shows the simulation results of the flows which are sorted according to the throughput of our metric RLCI. This figure also shows the gap between the practical throughput and the estimated available bandwidth.

We first analyze the differences between the results of the considered metrics. We can observe that with HC, throughputs are the smallest. Indeed, based only on distance, it is more likely to select overloaded and interfering paths with poor link quality for data transmission. ETX and ALM perform better compared to HC. However, we can observe that they do not work well in some cases

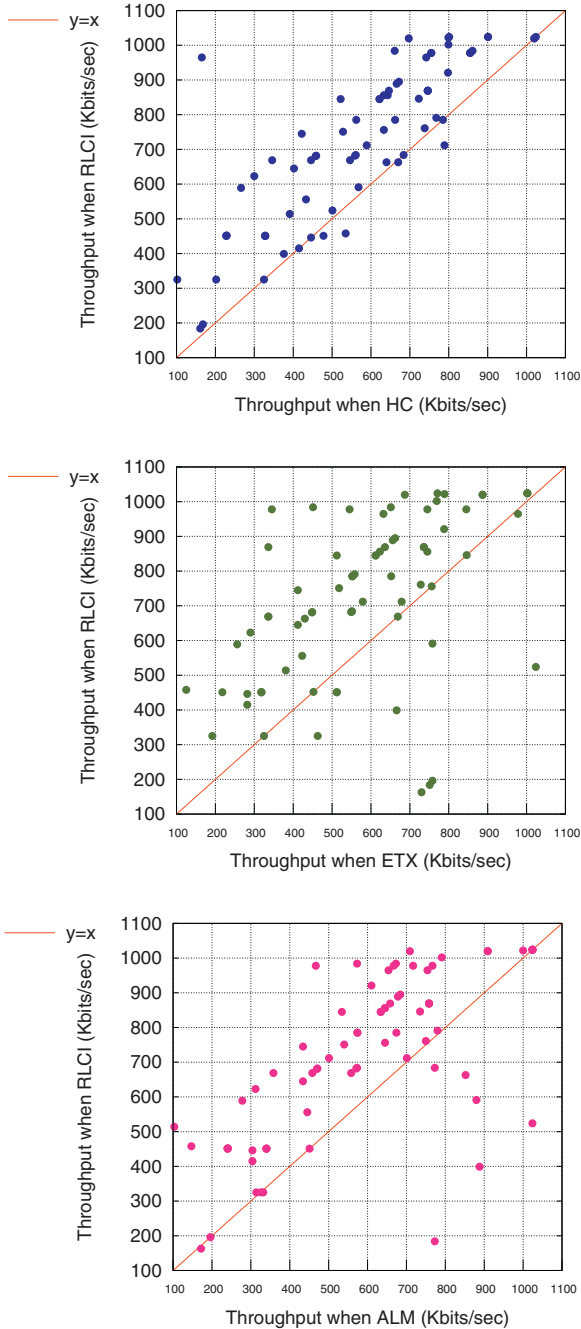


Fig. 8. Per pair cumulated throughput of RLCI, (a) compared to HC; (b) compared to ETX; (c) compared to ALM.

since ETX and ALM of a given path are both deduced from a simple addition of ETX and ALM of links forming the path. These metrics neglect the performance degradation caused by interference between successive links and may select a low available bandwidth path. Therefore, our metric is relatively more efficient for finding the high-throughput path. We now investigate why there is a difference between the practical throughput and the estimated available bandwidth. Fig. 8 shows that the practical throughput may be more than or less than the estimated one. First, our work develops an underestimate of the true available bandwidth because the theoretical calculation of our metric does not take into account of packet overheads and collisions in the MAC layer, which reduce the actual throughput in a real network. Another factor that leads to the practical throughput is less than the theoretical throughput is

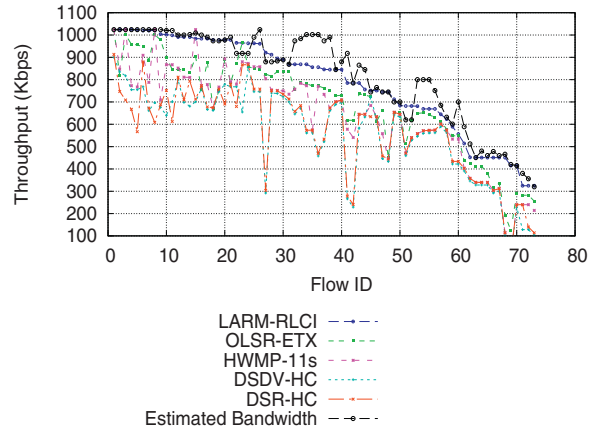


Fig. 9. Throughput of data flows.

Table 2
Simulation parameters.

Parameter	Value
Simulation duration	200 s
Topology	2500 × 2500 m
Number of nodes	20-40-60-80-100
Sensing range	250 m
Frequency band	2.4 GHz
Transmission power	30 dBm
Propagation model	Nakagami-m
Datarate	1Mbits/s
Packet size	1024 Bytes
Buffer size	100 packets
OLSR-Hello interval	2 s
OLSR-TC interval	5 s
RANN interval	3s
Proactive PREQ interval	3 s

the assumption on interference range. We assume 2-hop interference but situations like Fig. 1 can happen. The practical throughput is thus smaller than the estimated path bandwidth. On the other hand, simulation results show that our approach gives an overestimation for almost all of the flows with large hop-count distance which can be explained by the fact that our metric is still based on traffic history. This traffic can change from instantly and so, a given link could be more available after significant traffic i.e it offers greater real bandwidth than the estimated one.

5.2. Routing mechanism evaluation

In this section, we evaluate the performance of our routing mechanism LARM with comparison to other existing protocols. The study is done under different strategies and PHY and MAC parameters in order to study the possible interaction and coexistence of such protocols in a heterogeneous multi-rate mesh environment and this, to figure out if the choice of combining PHY/MAC/NWK could affect the overall network performance and why. We considered a multitude of combinations of the protocol stack as shown in Fig. 10.

Several proactive, reactive and hybrid routing protocols, implementing each a different routing metric, are considered : LARM(RLCI), DSR (HC), OLSR (ETX), DSDV (HC) and HWMP (ALM). We remind that HWMP is implemented at layer 2 but is considered here as a routing protocol for organizational reasons. Simulation parameters are given in Table 2.

End to end delay

Fig. 11 shows the average end to end delay for the various combinations while increasing the number of deployed nodes and the

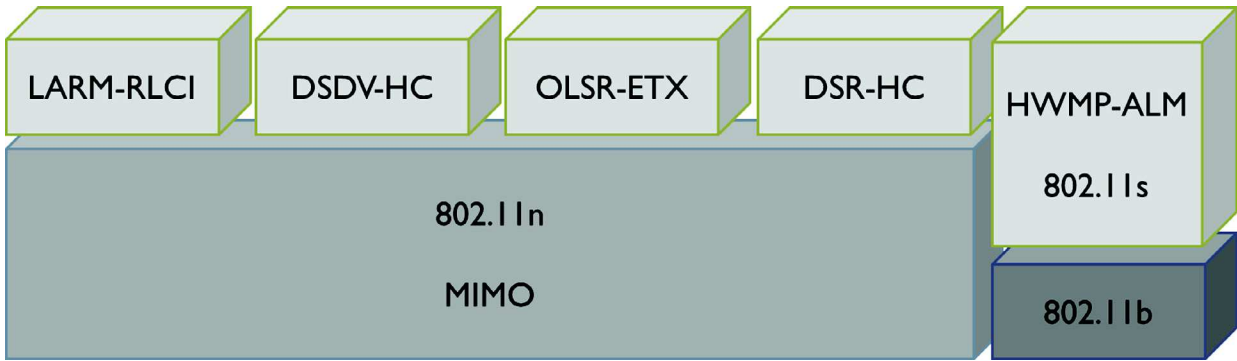


Fig. 10. Considered protocol stack.

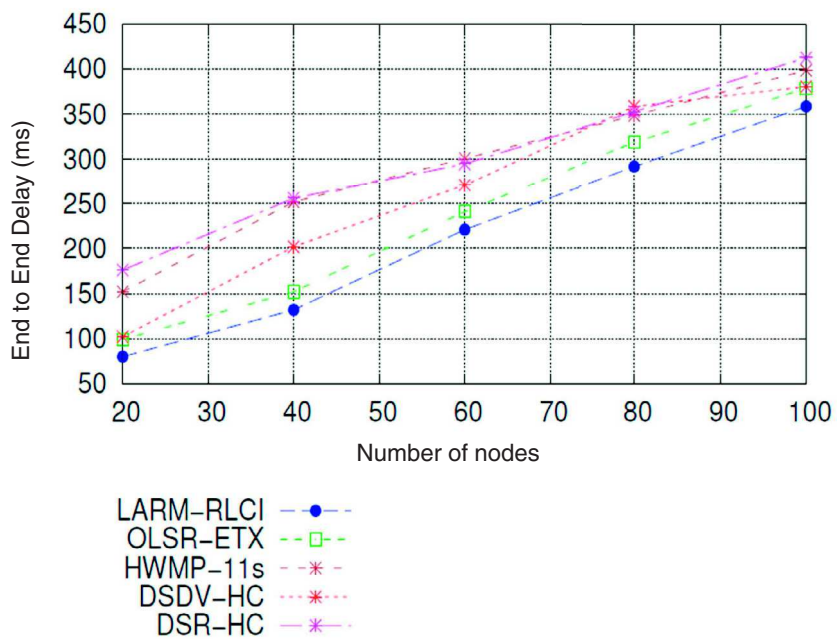
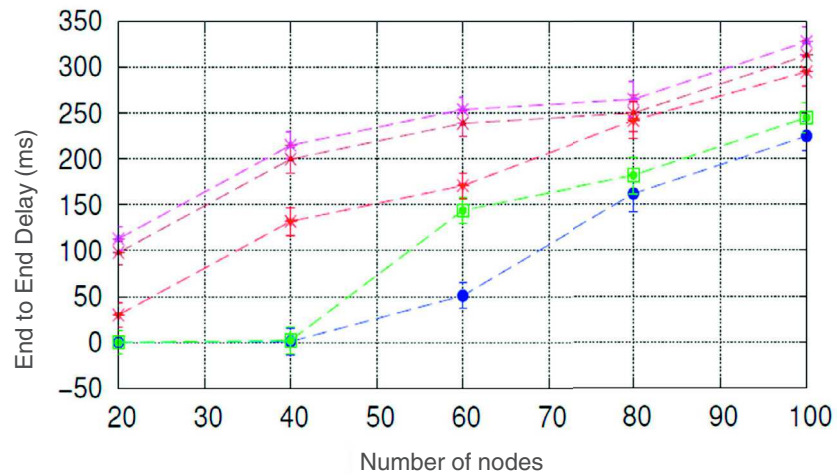


Fig. 11. End to End Delay evolution with the traffic charge : (a) low traffic; (b) important traffic.

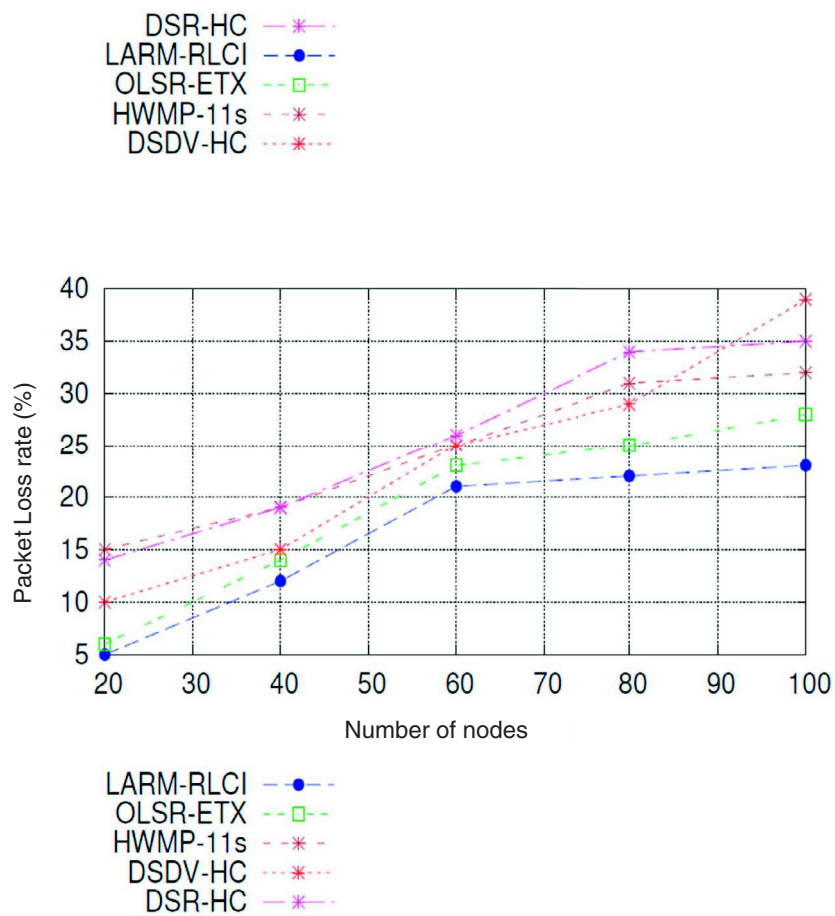
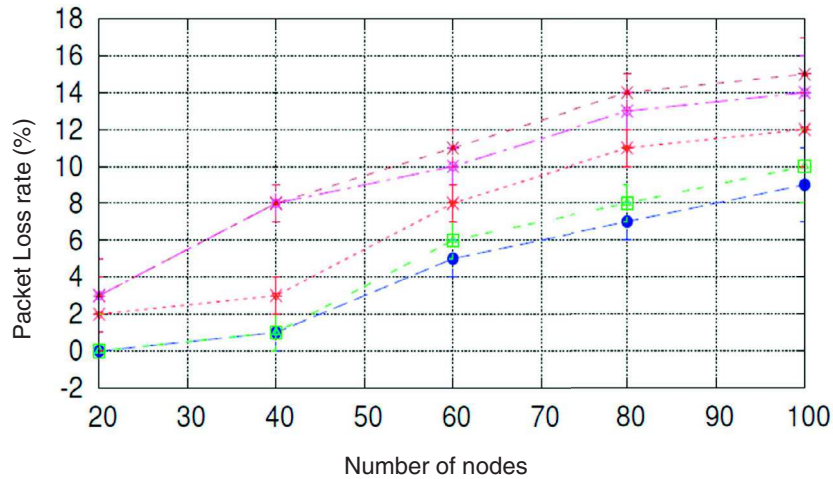


Fig. 12. Loss rate evolution with the traffic load : (a) low traffic; (b) important traffic.

traffic load in the network: low traffic if only 30% node pairs of the total number of deployed nodes are communicating, important traffic if 70%.

It identifies the average time between sending a packet from a transmitter node and receiving it by the destination node, in milliseconds. This period includes all potential delays caused by queues, delays at the MAC level, retransmission, radio propagation and transfer time.

The results show that, for all combinations, the end to end delay increases with the size of the network, because in general, increasing the number of nodes in the network, neighborhood changes and the number of hops be-

tween the source and the destination are also increasing. Thus, the delays caused by buffering delays and queues at intermediate nodes contribute significantly to the end to end delay.

This increase is particularly significant with DSR and HWMP protocols. This can be explained, from a routing point of view, on the one hand, by the reactive nature of these two protocols and particularly delays needed at each "route request" to establish valid routes. Moreover, since the DSR routing decision is based solely on the number of hops, this gives advantage to other protocols incorporating link quality metrics to achieve better performance particularly in terms of delivery delay.

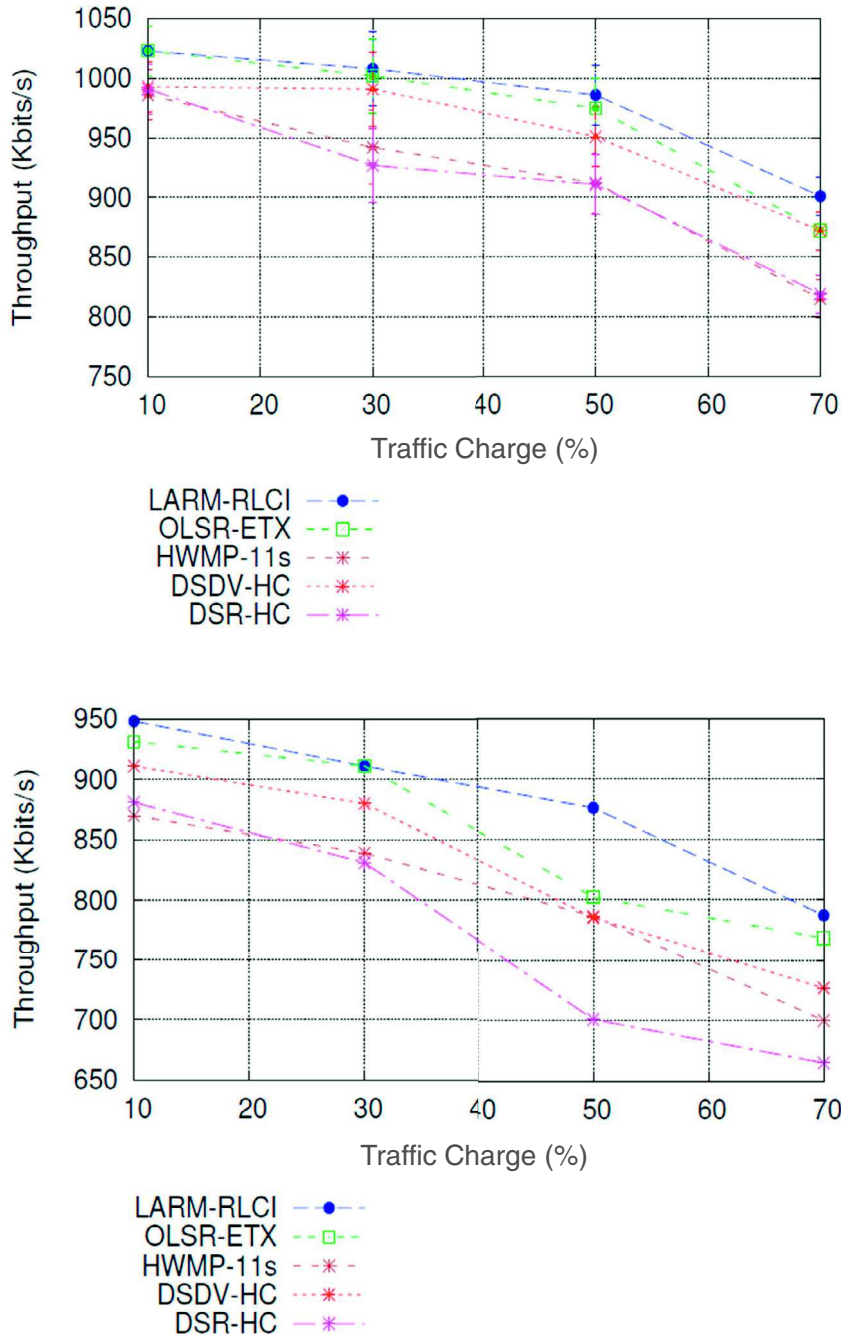


Fig. 13. Throughput for a network topology of : (a) 40 nodes; (b) 80 nodes.

For dense topologies, networks based on the IEEE 802.11n MAC layer and MIMO technology provide, in most cases, faster delivery. This is mainly due to the link capacity and high throughput offered by the physical layer. In all conditions and traffic density, our protocol LARM performs the best thanks to the RLCI metric which incorporates the diversity of rates and benefits from large link capacities and data aggregation mechanism of IEEE 802.11n MAC layer particularly in case of heavy traffic. Compared to OLSR, delay variation of our protocol LARM shows some similarity due to the proactive nature of both routing protocols. However, LARM, functioning with our metric RLCI, is more able to select widest paths and to ensure faster packet delivery. It offers an average end to end delay slightly lower than OLSR through its ability to borrow routes offering more throughput. Note that for the topologies of 20 nodes and

40 nodes, the values of the delays generated by LARM and OLSR are not null and are equal to, respectively, 0.921 ms and 1.756 ms for LARM and 0.927 ms and 2.276 ms for OLSR.

Loss rate

Fig. 12 shows the loss rate which is calculated from the number of lost data packets from all transmitted data packets. The results show that for all scenarios, the loss rate is affected by both the number of nodes and the traffic load.

In general, for low traffic, the loss rate is significantly affected by the routing decision. Routing protocols based on the hop count are less reliable because the shortest paths may contain saturated, interfering or breakable links causing, indeed, data corruption or packet loss.

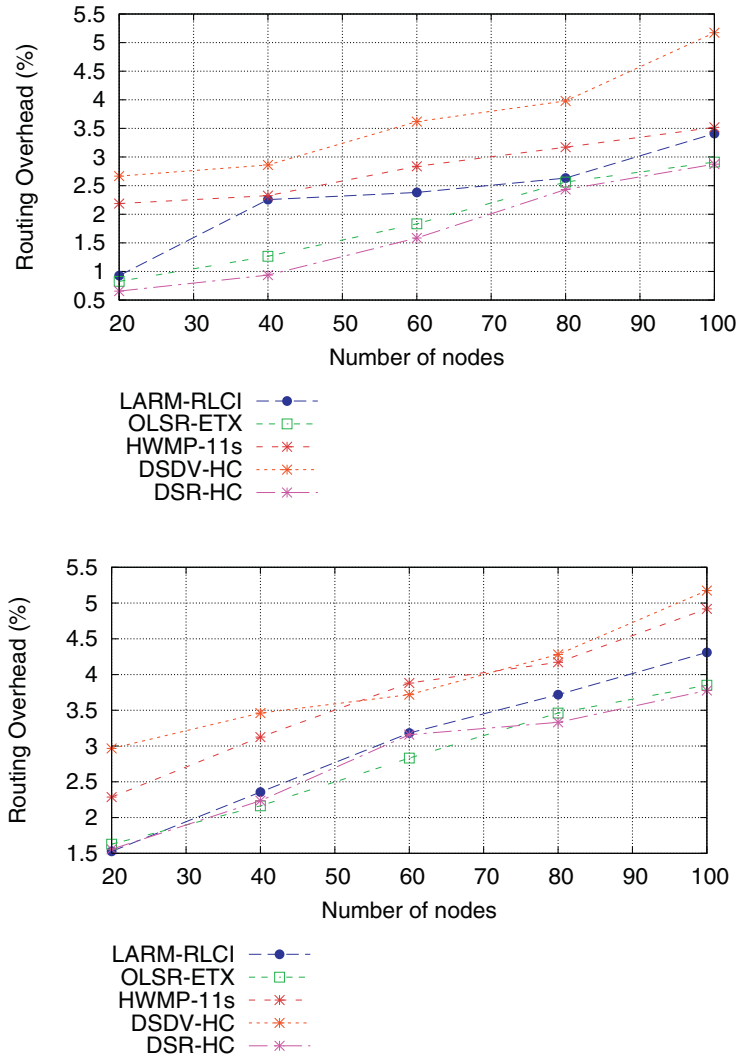


Fig. 14. Routing Overhead evolution with traffic charge. (a) low traffic; (b) important traffic.

Throughput

The average throughput is given in Fig. 13. It is expressed in kbits/s and measures the total number of bits of received packets during the simulation period. Since the throughput variation with the network density is not significant, we have chosen to represent the evolution of this performance criteria based on the traffic load which is more representative. We used two representative topologies namely, a 40 nodes network (see Fig. 13(a)) and a network of 80 nodes (see Fig. 13(b)).

Results show that, depending on the traffic load, the throughput decreases gradually. This decrease reflects the losses previously identified.

Our protocol LARM performs the best with an important traffic load. It maintains a good throughput longer because of his choice of the most available links offering the greatest rates. Routing protocols based on hop count prefer the shortest paths and therefore the network quickly suffers from congestion and there is no reaction to address this situation. OLSR achieved better results compared to DSDV and DSR, thanks to the capacity of its ETX metric to measure the link loss rate, therefore, to choose links with the greatest delivery rates. However, since the ETX estimation is based only on small probe messages, this may lead it to underestimate data loss.

HWMP performance is very similar to DSR with a slight improvement. Indeed, the metric ALM considers, in addition to the error rate, link capacities. But this value is theoretical only and corresponds to the total capacity of the link.

Routing overhead

Fig. 14 shows the normalized routing overhead. It is calculated from the number of transmitted control packets among delivered data packets.

The similar appearance of most results leads us to conclude that the PHY/MAC layers have no significant impact on this performance metric. From a routing point of view, we can note from these results a significant overhead generated by DSDV compared to other protocols and this independently of the lower layers and the traffic load. This disparity is due to the massive exchange of routing information particularly in dense networks. The HWMP protocol also suffers from a significant overhead since it uses both types of control messages (proactive tree based dissemination and reactive one).

The exchange of routing information between the different nodes of the network would be the main factor in the overhead. Indeed, in a proactive routing strategy, controlled dissemination as the use of MPR sets with OLSR, significantly reduces the num-

ber of control messages circulating in the network. LARM manages this overhead by using only triggered updates allowing it to generate less overhead compared to DSDV, but its performance is slightly lesser compared to OLSR, particularly in dense networks. Including the first 4 links of the path in the header of the data packet also generates additional overhead but remains negligible vis-a-vis the overhead induced by the exchange of routing tables. Since the calculation of this overhead is based solely on the number of messages, it can probably provide more degraded performance if the calculation was made according to the size of control messages.

The routing metric slightly affects this overhead. Indeed, as ETX and ALM use control messages for collecting routing data for the calculation of the metric which can be a source of additional overhead when there is important traffic or in case of a dense network. With its cross-layer mechanism, our protocol LARM avoids this source of overhead.

5.3. Synthesis

Performance evaluation conducted on the ns-3 simulator showed, in general, good performance of our metric RLCI incorporated into the protocol our LARM. In terms of end to end delay, our metric can choose links offering high throughput and enabling faster delivery of data packets. Coupled with a MAC layer offering high heterogeneous capacities, our routing mechanism reached, in most scenario and topologies, relatively brief delays compared to other protocols and metrics. By focusing on the less loaded links, our routing solution prevents the formation of bottlenecks which is usually the main cause of data loss. This feature explains the results of loss rate which remains fairly low compared to other solutions even in dense network and/or heavy traffic. The advantage of our metric in terms of throughput is double effect: first, our metric calculates the widest path toward a destination and gives a guarantee on the rate offered for each data transmission. On the other hand, the metric RLCI considers both intra-flow and inter-flow interferences, which permits a proper, accurate and continued estimation of available bandwidth on the network. By exploiting these aspects, the routing strategy based on this metric RLCI acquires adaptability to network scalability in terms of topology and load and thus offers QoS guarantees for terminal nodes.

However, in terms of overhead, our routing solution requires a significant exchange of routing information to ensure a coherent and unified view of available resources on the network. This overhead is inevitable but can be managed if we properly choose the parameters of our metric RLCI. Indeed, the overhead factor strongly depends on the update frequency of routing information on the network. This parameter represents a compromise between the accuracy of the calculated information and broadcasting costs of this information. For this purpose, we have provided, in a further work, a detailed study of this factor to measure its impact on the efficiency of our routing solution.

6. Conclusion

In this paper, we investigated the maximum available bandwidth path problem, which is an important issue to support quality-of-service in wireless mesh networks. We exploited PHY and MAC characteristics of the IEEE 802.11n layer to design an efficient routing metric that estimates the available path bandwidth when taking into account both intra-flow and inter-flow interferences.

Our metric measures, first, the residual link capacity in order to address the ability of links to support additional traffic and thus prevent the creation of bottlenecks. The route selection is based on the evolution of this metric over time. Based on the conflict

graph model and calculation of maximal cliques, we proposed a method to estimate the available bandwidth when accounting for the neighborhood interferences. Finally, we defined a routing protocol that supports this metric.

Our solution also exploits link-diversity to perform load-balancing at each wireless hop by spreading the traffic load of the incoming flow on multiple concurrent links while considering intra-flow interference.

The performances of this protocol were evaluated by simulation with comparison to other existing routing metrics and protocols (DSR-HC, OLSR-ETX, HWMP-ALM, DSDV-HC). Results showed substantial performance improvements compared to different existing routing protocols and metrics specially in terms of delay and throughput.

The isotonicity property of the routing metric would improve the efficiency of our solution particularly in terms of overhead, for that reason we propose in a further work, to study the feasibility of an isotonic path weight based on our RLCI metric. It might be interesting, also, to adapt our routing solution to an application taking advantage of a multi-channel context. In this case, one should distinguish interference on the same transmission channel to those that may occur on adjacent channels.

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