Routing Metric for Interference and Channel Diversity in Multi-Radio Wireless Mesh Networks

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Abstract. More than providing a wireless structure for Internet access, Wireless Mesh Networks are being challenged to support diverse kinds of multimedia applications such as Voice over IP and video streaming in publish-subscriber and peer-to-peer service models. In this context, several routing metrics have been proposed to improve the routing performance as well as the network capability to satisfy the requirements of multimedia applications. However, most routing metrics lack the consistent integration of efficient monitoring mechanisms for interference and traffic load characterization in order to support the adequate decisions by the routing algorithms. In this sense, a new routing metric is proposed in this paper, called Metric for INterference and channel Diversity (MIND), that measures network interference and load, based on a passive monitoring mechanism in order to avoid the overhead of active network state information gathering. An evaluation of MIND and relevant existing routing metrics was performed using NS2. The results showed that when path selection is based on MIND, traffic performance is significantly better than with the other metrics.

Keywords: Wireless Mesh networks, interference-aware routing metric, isotonicity, passive monitoring and traffic load estimation.

1 Introduction

Wireless Mesh Networks (WMNs) are multi-hop wireless networks with self-organization capability that provide low cost solutions for ubiquitous Internet access. WMNs comprise Mesh Clients (MCs), Mesh Routers (MRs) and Mesh Gateways (MGs). A set of MRs forms the WMNs backbone that offers connectivity to the Internet for MCs. Usually, MRs are stationary and do not have energy constraints [1]. In addition, MRs can employ Multi-Channel Multiple-Radio (MCMR) capability [1, 2] to achieve an improved performance. With MCMR, each radio is associated with its own MAC and physical layer. Therefore, a MCMR empowered WMN has better potential to scale as the size of the network increases [3].

Quality of Service (QoS) provisioning has become important in WMNs for the support of multimedia applications such as Voice over IP (VoIP) and Video. In

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this context, path selection plays a key role. For this purpose, routing protocols, algorithms and metrics have been developed to enhance WMNs performance [4].

Since several nodes share the wireless medium, a wireless link in WMNs does not have dedicated bandwidth and consequently, neighboring node transmissions may compete for the same bandwidth interfering with transmissions of neighboring links. Therefore, in order to select paths that satisfy requirements for multimedia applications, the routing process must be aware of the link quality and traffic load so that it captures the interference between neighboring nodes and links with heavy traffic. For this reason, the routing metric needs to combine information about interference and load in the wireless link, while avoiding introducing excessive overhead due to the measurement and distribution of this information. In order to gather information from different layers, a cross-layer design is usually employed [5, 6].

There are two interference models that have been studied in the literature, namely, protocol and physical interference models [7]. The protocol interference model determines that a transmission from a node A to a node B is successful if (i) there exists a link between them in the network topology, which is used for the transmission; and (ii) any node C such that $d_{CB} \leq R$ or $d_{CA} \leq R$ is neither transmitting nor receiving in the channel used by A and B. d_{CB} represents the distance between nodes C and B, and R represents the interference range, which for simplicity is assumed to be the same for all the nodes. Therefore, channel assignment algorithms have been adopted in MCMR WMNs in order to assign the available channels to radio interfaces of mesh routers, minimizing the overall interference [8].

The physical interference model captures the interference experienced by wireless links in the WMNs. In this model, a communication between nodes k and l is successful if the Signal to Interference-plus-Noise Ratio (*SINR*) at the receiver l is above a certain threshold which depends on the desired transmission characteristics, such as channel and data rate. Furthermore, the physical model is less restrictive compared to the protocol model, since it only depends on the signal strength values, such as Signal-to-noise ratio (*SNR*) and SINR, whereas the protocol model uses the concept of transmission range and interference range. It has the advantage of measuring the parameters of the model using on-line data traffic.

In addition, the restricted number of channels available in the IEEE PHY specification [9] does not permit to assign one channel for each wireless link in the WMN (for instance, the simultaneous operation of three non-overlapping channels in the 2.4 GHz band and 12 non-overlapping channels in the 5 GHz band). Therefore, channels are assigned in a repetitive way among the links and therefore, there will be interference among some links. For these reasons, the routing decision helps to reflect the actual link quality if it is based on the physical interference model. Summing up, interference-aware routing metrics are more suitable to WMNs, since they capture the link quality in a more realistic way.

Since many MCs may access the Internet to use multimedia applications provided by external servers, the traffic might mainly flow towards or from the MGs. Thus, the routing metric also needs to consider the traffic load in order to balance the load on the entire WMNs. Furthermore, due to the restricted resources of the wireless networks, it is desirable to use routing metrics that are based on passive monitoring mechanisms. A passive metric should provide a sufficiently accurate link representation that allows a routing algorithm to select high quality paths as well as eliminate the overhead associated with active monitoring techniques. For these reasons, in this paper, a new routing metric based on cross-layer design is presented, called as Metric for INterference and channel Diversity (MIND). MIND is then used by the Optimized Link State Routing (OLSR) protocol [10] for path selection.

This paper is organized as follows. Section 2 describes related work about routing metrics for WMNs. The proposed routing metric is presented in Section 3 as well as the implemented mechanisms in order to satisfy the requirements of the metrics in the WMNs. Section 4 describes the simulation study comparing MIND with relevant existing routing metrics. Finally, Section 5 presents, conclusions and issues to be addresssed in future work.

2 Related Work

This section presents the main routing metrics for Wireless Mesh Networks.

The Expected Transmission Count (ETX) [11] is defined as the expected number of MAC layer transmissions that is needed to successfully deliver a packet through a wireless link. The weight of a route is defined as the total sum of the ETX of all links along the route. This metric takes into account both packet loss ratio and route length. Moreover, ETX is also an isotonic routing metric, which guarantees calculation of minimum weight paths and loop-free routing [12]. If Bellman-Ford or Dijkstra's algorithms are used in hop-by-hop routing, isotonicity is a necessary condition to calculate the minimum weight paths. Nevertheless, ETX does not take into consideration interference and different links that may have different transmission rates.

The Expected Transmission Time (ETT) [13] routing metric improves ETX by considering the differences in link transmission rates. Namely, ETT is defined as the amount of time that is needed to transmit a packet through the link. The weight of a path is the sum of the ETT of all links on this path. This metric is also isotonic. Nevertheless, it has a drawback, since it does not fully capture the intra-flow and inter-flow interference in the network. For example, ETT may result on a route that uses only one channel, although a route with more diversified channels, and thus with less intra-flow interference, is available.

The Weighted Cumulative Expected Transmission Time (WCETT) [14] routing metric was proposed to reduce the number of nodes on the route of a flow that transmit on the same channel. WCETT captures the intra-flow interference of a route since it gives low weight to paths that have more diversified channel assignments on their links and hence lower intra-flow interference. Notwithstanding, it does not consider the effects of the inter-flow interference. Hence, WCETT may route flows to dense areas where there is congestion and may even result in starvation of some nodes due to congestion. Furthermore, WCETT is not isotonic and consequently prevents the use of an efficient loop free routing algorithm to compute minimum weight paths [14].

The Metric of Interference and Channel-switching (MIC) [15] improves WCETT by overcoming its non-isotonicity and its inability to capture inter-flow interference. MIC estimates inter-flow interference measuring the number of links that can interfere in the transmission. Namely, MIC does not consider interference in a dynamic way, which is a limitation, since the interference can change over time due to signal strength variations and to the amount of traffic generated by the interfering nodes.

The interference-AWARE (iAWARE) [16] routing metric aims to support the computation of paths that have lower inter-flow and intra-flow interference than MIC, WCETT and ETT. This metric resorts to SNR and SINR to continuously reproduce neighboring interference variations onto routing metrics and therefore, being based on the physical interference model. iAWARE employs a correlation between (SINR/SNR) and ETT, thus, capturing the effects of variation in link loss-ratio, differences in transmission rate, as well as inter-flow and intra-flow interference, in a dynamic way. However, iAWARE is not isotonic. The iAWARE and WCETT non-isotonicity is demonstrated in [15].

Despite the improvement from ETX to iAWARE, all the metrics discussed employ AdHoc probing (i.e., active monitoring) that sends fixed size packet-pairs (e.g., 1000 bytes) in order to estimate the delay [17]. This mechanism causes an excessive overhead and therefore, it might not scale in large or high density networks. In addition, active techniques need to access the medium, which may be difficult if the links are congested. For this reason, Resource Aware Routing for mEsh (RARE) was proposed [18], which uses a passive monitoring technique that combines available bandwidth, signal strength and average contention in the same link cost function. Nevertheless, RARE's performance is equivalent to ETT and there are even some situations where ETT outperforms RARE.

Recently, improvements of the ETX and ETT metrics were proposed, such as Interferer Neighbors Count (INX) [19] and Contention-Aware Transmission Time (CATT) [20]. Similarly to MIC, INX takes into account interference through the number of links that can interfere on link l and their data rates. This metric presents better performance with low load. In addition, CATT captures the influence that the interfering links, in 1 and 2 hop neighbors, can have on the needed time to transmit a packet over link l. Therefore, the use of CATT avoids the congested paths and has better performance than MIC, ETT and ETX. Nonetheless, these metrics still use a probing mechanism and do not consider interference in a realistic way, as explained before.

Table 1 summarizes related work on routing metrics, according to the main requirements, e.g. interference awareness, load awareness, isotonicity and probing mechanism. The analysis of this table shows that existing solutions address only some specific requirements and fail to provide interference and load awareness

Table 1. Related Work on Routing Metrics

Related Work	Interference-Aware	Load-Aware	Isotonic	Passive Monitoring
ETX [11]	No	No	Yes	No
ETT [13]	No	No	Yes	No
WCETT [14]	No	No	No	No
MIC [15]	Yes	No	Yes	No
iAWARE [16]	Yes	No	No	No
RARE [18]	No	No	Yes	Yes
INX [19]	Yes	No	Yes	No
CATT [20]	Yes	Yes	Yes	No

using passive monitoring while achieving isotonicity. For this purpose, a new routing metric is proposed in order to simultaneously address all these aspects.

3 MIND - Metric for INterference and Channel Diversity

This section presents the MIND routing metric. The MIND metric includes two components, one that concerns inter-flow INTERference and LOAD awareness ($INTER\_LOAD$) and the other that captures intra-flow interference, called Channel Switching Cost (CSC). Moreover, MIND employs a virtual network to achieve isotonicity (Virtual nodes will be explained in sub-section 3). Hence, Bellman-Ford or Dijkstra's algorithms can be used to find out the minimum weight paths. $MIND$ is defined as follows:

$$MIND(p) = \sum_{linki \in p}^{n} INTER\_LOAD_i + \sum_{nodej \in p}^{m} CSC_j \tag{1}$$

where n is the number of links and m is the number of nodes of the path p.

As it can be seen in Equation 2, the rationale behind the $INTER\_LOAD$ normalization is that it depicts information about interference and traffic load simultaneously and therefore, this information can be used on the path selection. For this purpose, Interference Ratio (IR) is employed to capture the interference among links based on the physical interference model [16, 21]. Therefore, MIND mainly considers interference whereas using Channel Busy Time (CBT) as a smooth function of multiplicative weighted over IR. Thus, it allows a trade-off between interference and load balancing in which interference has higher weight than traffic load. τ, a configurable parameter, is used to provide a higher weight to interference in the $INTER\_LOAD$ component.

$$INTER\_LOAD_i = ((1 - IR_i) * \tau) * CBT_i \tag{2}$$

where $0 \leq IR \leq 1$ and $0 \leq CBT \leq 1$.

The IR sub-component depicts the interference based on the ratio between $SINR$ and SNR. Thus, this sub-component takes into consideration interference through the signal strength values which can be measured using commodity wireless cards. It also relies on a passive monitoring technique to capture the $SINR$ and SNR values without additional traffic, in contrast to routing metrics proposed which use special kind of traffic (e.g., probe packets) to measure the degree of interference between links [15, 20]. It is worth noting that when there is no inter-flow interference (i.e., no interfering neighbors or no traffic generated by interfering neighbors) $SINR$ of link i is equal to the SNR and thus IR_i is 1. In this case, the link i is independent of inter-flow interference and the quality of the link is determined by the intra-flow interference component. A more detailed description about the SNR formulas and $SINR$ is presented in [16]. Equation 3 shows the IR ratio.

$$IR_i = \frac{SINR_i}{SNR_i} \tag{3}$$

CBT is the most direct and passive metric to measure the channel utilization in wireless networks [6, 22]. Therefore, the estimation of the traffic load is based on CBT, according to Equation 4. The CBT calculation is based on the time that packets spend in a wireless medium for a successful transmission. Namely, it uses a complementary calculation through the idle period. The $IdleTime$ value (Equation 4) considers the backoff times and time that no data keeps the channel busy. Instead of using the current value of a single packet, CBT is smoothed through the CBT average of the last 20 packets (this value is based on an empirical study - the detailed analysis performed is not presented here due to lack of space) in order to improve reliability and reduce the probability of CBT oscillations. The smoothing function is also used in IR values.

$$CBT_i = \frac{TotalTime - IdleTime}{TotalTime} \tag{4}$$

MIND uses the CSC component to reduce the intra-flow interference. With this approach, paths with consecutive links using the same channel have higher weight than paths that alternate their channel assignments, essentially favoring paths with more diversified channel assignments. Equations 5 describes the CSC component.

$$CSC_j = \left\{ \begin{array}{l} w1 \text{ if } CH\left(prev\left(j\right)\right) \neq CH\left(j\right) \\ w2, \text{ if } CH\left(prev\left(j\right)\right) = CH\left(j\right) \end{array} \right\} \tag{5}$$

where $0 \leq w1 < w2$, $CH(j)$ represents the channel assigned for node i's transmission and $prev(i)$ represents the previous hop of node i along the route p.

MIND is an isotonic interference-aware routing metric that considers the inter-flow interference in a more realistic way, intra-flow interference based on the local information and traffic load estimation through passive monitoring. The virtual network decomposition is described in the following sub-section.

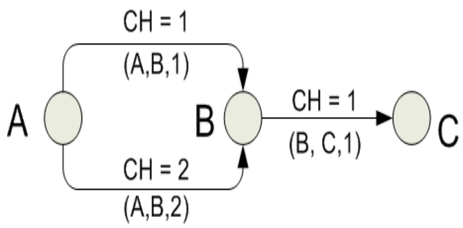

Fig. 1. MIND without Virtual Network [15]

Decomposition of MIND into a Virtual Network: MIND employs a virtual network scheme in order to become isotonic [15]. Figure 1 shows that the non-isotonic behavior of MIND is due to the fact that the additional weight that link $(B, C, 1)$ brings to a path not only depends on link $(B, C, 1)'s$ own status, but it is also related to the channel assignment of the link that precedes link $(B, C, 1)$. Due to the common channel used by links $(A, B, 1)$ and $(B, C, 1)$, adding link $(B, C, 1)$ to path $(A, B, 1)$ introduces a higher cost than adding link $(B, C, 1)$ to path $(A, B, 2)$. Hence, even though $MIND((A, B, 1)) < MIND((A, B, 2))$, $MIND((A, B, 1) \oplus (B, C, 1)) > MIND((A, B, 2) \oplus (B, C, 1))$, where $\oplus$ indicates a link concatenation.

By introducing several virtual nodes to represent these possible channel assignments for the precedent link, MIND can be translated into isotonic weight assignments to the links between these virtual nodes. Namely, for every channel c that a node $A's$ radios are configured to, two virtual nodes $A_i(c)$ and $A_e(c)$ are introduced. $A_i(c)$ represents that node $prev(A)$ transmits to node A on channel c. $A_e(c)$ indicates that node A transmits to its next hop on channel c.

Figure 2 shows an example of the virtual nodes for nodes A, B and C. Links from the ingress virtual nodes to the egress virtual nodes at node A are added and the weights of these links are assigned to capture different CSC costs. In addition, two additional virtual nodes are introduced, A+ and C- that are the start and end points, respectively.

Link $(A_i(c), A_e(c))$ means that node A does not change channels while forwarding packets and hence weight $w2$ is assigned to this link. Similarly, weight $w1$ is assigned to link $(Ai(c), Ae(c1))$, where $c \neq c1$, to represent the low cost of changing channels while forwarding packets. Links between the virtual nodes belonging to different real nodes are used to capture the $INTER\_LOAD$ weight. By building the virtual network from a real network, MIND is essentially decomposed in the real network into weight assignments to the links between virtual nodes. This is because the MIND weight of a real path in a real network can be reconstructed by aggregating all of the weights of the virtual links on the corresponding virtual path. The $INTER\_LOAD$ part of MIND is reflected in the weight of the links between virtual nodes in different real nodes. The CSC costs are captured by routing through different virtual links inside real nodes. Table 2 illustrates the real network mapping into the virtual network.

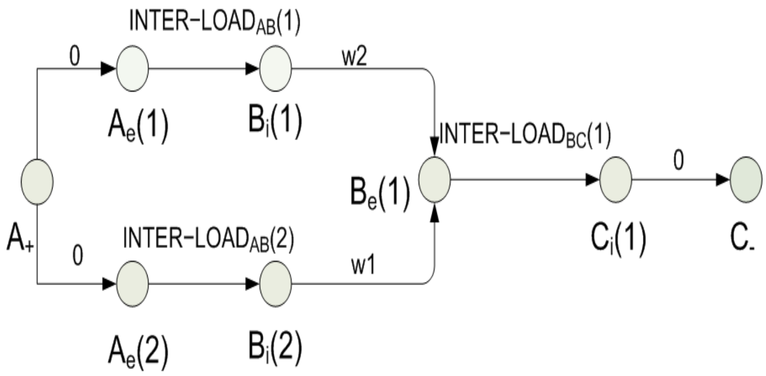

Fig. 2. Virtual Network of MIND

Table 2. Real network mapping to the virtual network

Real Path	Virtual Path	MIND weight
$(A, B, 1) \oplus (B, C, 1)$	$A_e(1) \rightarrow B_i(1) \rightarrow B_e(1) \rightarrow C_i(1)$	$INTER\_LOAD_{AB}(1) + INTER\_LOAD_{BC}(1) + w2$
$(A, B, 2) \oplus (B, C, 1)$	$A_e(2) \rightarrow B_i(2) \rightarrow B_e(1) \rightarrow C_i(1)$	$INTER\_LOAD_{AB}(2) + INTER\_LOAD_{BC}(1) + w1$

The iAWARE and WCETT non-isotonicity is caused by the dependence of the intra-flow interference component that captures the channel assignment of all links in a path. Namely, the weight increment of adding a link l to a path p depends on how many times each channel has appeared in path p. As the length of p increases, the combination of channel assignments can become infinite and therefore, iAWARE and WCETT cannot be decomposed into virtual networks. Moreover, a node usually does not interfere with other nodes that are more than two hops away even if they share the same channel. A detailed description about the WCETT non-isotonicity is described in [15]. Contrarily to these metrics, MIND uses local information to reduce intra-flow interference.

OLSR extension for Virtual Network: CSC needs to be computed in order to correctly implement the virtual network in the OLSR routing protocol. The implementation of the virtual network resorts to two different components, the extension of the information residing in the routing control messages that aggregate hello and topology control messages, and the weight calculation (i.e., $w1$ and $w2$). The control packet is enhanced with information about the previous CSC value and about the arriving interface. Since this information is not available at the routing layer, the calculation of the weights is computed in the forwarding phase of the OLSR routing protocol. Therefore, and following the specified schema by [15], if a control packet is originated from the current node, the CSC is not calculated (i.e., CSC is equal to zero), as any interface chosen will give the lowest CSC value.

On the other hand, if the control packet is destined to the current node, the CSC is not calculated, as it will not be forwarded again. When the node has to forward a control packet not originating from it, it will use the incoming interface to find the best route according to the routing table. If the chosen route corresponds to a different interface, the metric will have a lower penalization than when using the same interface, and the new CSC value will be updated in the packet information. This way, the different states of the virtual network can be reached, depending on the previous and next steps to take, as well as making sure that new packets and packets that have reached their destination will follow the proposed schema.

4 Experimental Results

This section presents the performance evaluation of MIND and compares the results obtained with the CATT, INX, iAWARE, MIC, ETT and ETX routing metrics. To the best of our knowledge the work presented in this paper is the most thorough evaluation of WMNs routing metrics. These metrics were implemented in the OLSR protocol using the NS-2 simulator version 2.31 [23]. Table 3 shows the simulation parameters used [24].

Table 3. Simulation Parameters

Parameter	Value
Network Size	50
Topology Size	$1000m^2$
Transmission Range	250m
Interference Range	500m
Propagation Model	TwoRayGround
CBR Source Data Rate	8Kb/s
Simulation Time	60s
τ	10
Data Channel rate	2Mbps
PHY Specification	802.11 b/g
Antenna	Omnidirectional
Runs	10

The routing metrics were evaluated according to different parameters, such as throughput, delay, loss and jitter and under different loads, in a random topology. Source and destination flows were predefined in the network so that they intersect each other and consequently, cause a higher interference among data flows. All nodes have the same physical configuration. Figures 3 and 4 show

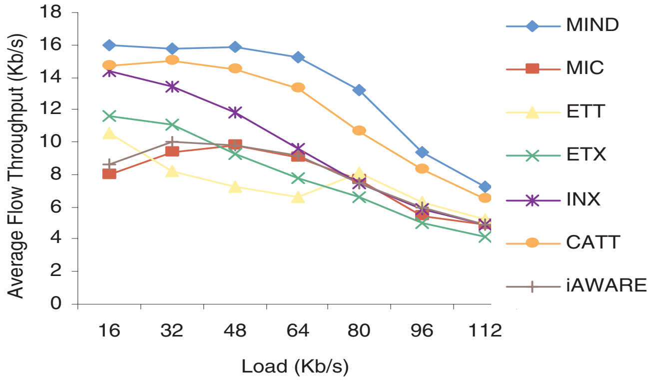

Fig. 3. Throughput

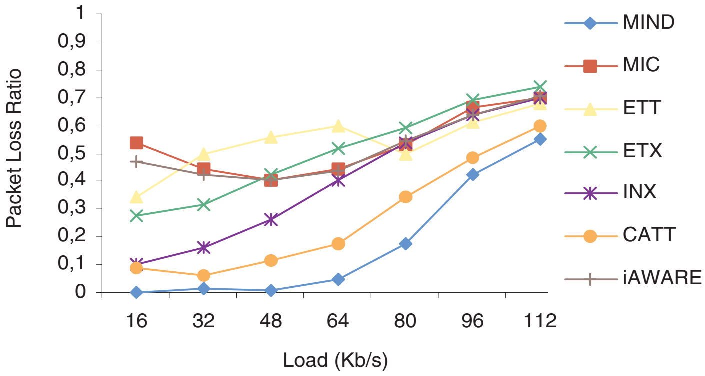

Fig. 4. Packet Loss Ratio

that MIC and iAWARE have worse throughput and loss ratio than ETT, ETX and INX with low loads (16 and 32 Kb/s).

However, the results of MIC and iAWARE improve as the traffic load increases and consequently, MIC and iAWARE have higher throughput and lower loss ratio than ETT, ETX and INX with medium and high loads. iAWARE and MIC have similar results, as expected. However, in some cases, iAWARE has a slight performance improvement over MIC, since iAWARE considers interference in a more realistic way. ETX and INX have better throughput and loss ratio with low loads, and decrease significantly their performance in high loads.

ETT presents an unstable behavior due to the probing technique that overestimates the link quality. Moreover, ETT does not depend on the traffic load, as was already assessed in [20, 25]. Although MIC and iAWARE rely partially

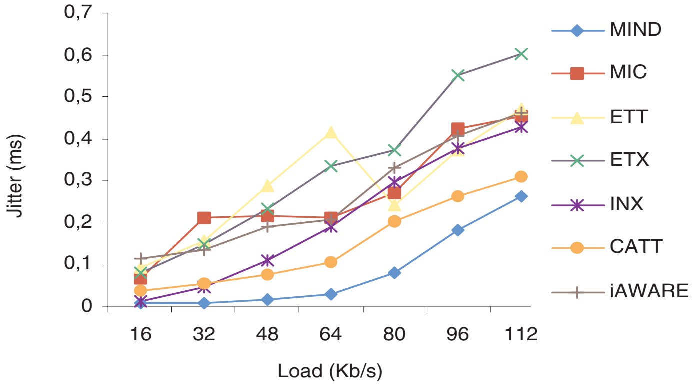

Fig. 5. Jitter

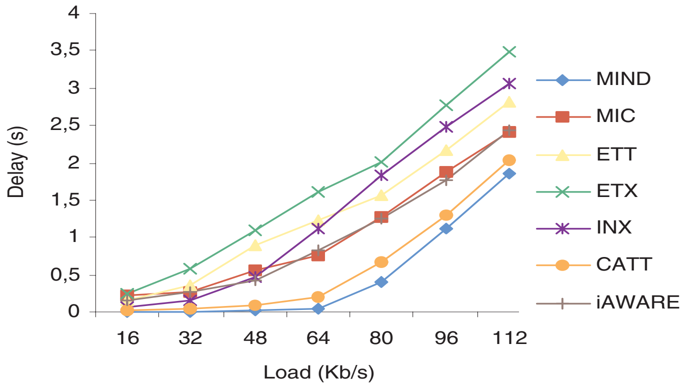

Fig. 6. Delay

on ETT, these metrics employ normalization functions to smooth the ETT values and therefore become more stable. Overall, CATT achieves better results than MIC and iAWARE for all loads, due to the avoidance of congested paths, achieved through the traffic load estimation.

Figures 3, 4, 5 and 6 show that MIND is able to achieve higher throughput, lower loss ratio, lower delay and lower jitter than the remaining metrics for all loads considered. Table 4 shows the MIND performance gain over the other metrics.

MIND has better performance than CATT for all loads and parameters considered. These results are due to the fact that MIND considers interference and traffic load in a more realistic way and uses passive monitoring. The difference of performance between MIND and CATT decreases for high loads (96 and 112 Kb/s), since the wireless medium resources become very scarce and thus, the impact of the routing metric becomes negligible.

Table 4. MIND Performance Gains

Metrics	Throughput	Loss	Delay	Jitter
ETX	67%	192%	241%	297%
ETT	77%	210%	166%	248%
MIC	71%	206%	113%	271%
iAWARE	65%	197%	106%	229%
INX	37%	130%	166%	149%
CATT	11%	52%	26%	79%

There are several characteristics that motivate a better performance of the MIND in all evaluated loads and parameters compared with the other metrics. MIND is an isotonic metric that allows routing algorithms to select minimum weight paths; it takes into consideration interference in a more realistic way through the physical interference model; it has a lower overhead due to lack of probe packets in order to estimate the traffic load; and lastly, it provides better load balancing among paths during the routing process due to the channel busy time component.

5 Conclusions and Future Work

This paper discussed the main aspects needed to design efficient routing metrics for multi-radio WMNs. After the identification of the relevant characteristics which are not provided by existing metrics, a new routing metric was proposed and implemented, called as Metric for INterference and channel Diversity (MIND), this metric considers several aspects that improve the WMNs performance, such as the selection of paths providing reduced inter-flow and intra-flow interference and the avoidance of overhead caused by active probing techniques. In addition, the MIND metric is isotonic which allows its employment with existing routing algorithms to select minimum weight paths and to avoid routing loops. MIND was evaluated in the NS2 simulator, using the OLSR routing protocol.

The results showed that MIND outperformed the most relevant routing metrics for WMNs. It is evidenced that MIND has better performance for all loads in the network and hence, it improves the network scalability. For example, an improvement of 26% and 79% in delay and jitter, respectively, when compared to CATT was obtained.

In the future, new correlations with differents information to improve MIND performance as well as virtual network extensions in order to simplify implementation of this scheme will be investigated.

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