Interference-Aware Routing Supporting CARMNET System Operation in Large-Scale Wireless Networks

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***Abstract*—The paper provides the research results concerning interference-aware routing metrics supporting the operation of large-scale wireless mesh/multi-hop networks. In particular, the description of state of the art in this domain of research has been provided and used in order to define a new interference-aware metric for multi-radio networks. The proposed solution is aimed at supporting traffic control mechanisms for multi-hop wireless networks by improving performance of any system controlling multi-hop wireless transmission, e.g., a system widening the access to the Internet by means of wireless communication such as a CARMNET system. Moreover, the paper presents the implementation of a set of tools necessary to provide experimental evaluation of the solution in a large-scale wireless environment as well as a set of tests comparing the performance of the proposed metric with state-of-the-art solutions. The experiments have been performed in the DES-Testbed located at Freie Universität Berlin, which is one of the largest wireless testbeds in Europe. Each of the nodes taking part in experimentation has a CARMNET Loadable Linux Kernel Module (CARMNET LLKM) deployed.**

Keywords*–*wireless mesh/multi-hop networks; interference-aware routing; large-scale wireless experimentation.

I. INTRODUCTION

Wireless networks are more and more popular due to the rise of mobile devices. While their capacity is much lower than capacity of their wired counterparts, they are highly valued by end users for ease of setup and unrestrained mobility. Mesh networks technologies, however, while very promising in theory are still underused by industry due to their complexity. In order to operate correctly, robust mesh networks require additional protocols for dynamic routing, resource allocation, and self-configuration.

The presented research has been motivated by the need for routing optimization necessary to improve the performance of a CARMNET resource management system operation [1] in large wireless networks. With the development of Wireless Mesh Network (WMN) the importance of routing protocol becomes more and more apparent. The interference-aware routing metrics which take advantage of wireless networks' properties, are especially important for the WMN researchers. One of the weaknesses of a multi-hop mesh network is self-interference, because of which, even in a scenario with a single transmitting node, the available bandwidth is much lower than that achievable throughput on the single link. More complex WMNs mitigate this problem by incorporating multi-radio nodes, allowing multiple transmission to occur at the same time without interference. For such networks, the development of special routing path metrics which take advantage of the non-interfering channels has to be provided. It has to be stressed that for such solutions interference range is still vague and certainly not limited to the 1-hop neighborhood. Moreover, the metrics have to provide the trade off between their complexity and achievable gains to make them practical enough for the implementation in real-world scenarios.

The goal of this paper is to provide the routing solution for large-scale multi-hop multi-radio wireless networks which is suitable to support the operation of resource management mechanisms based on utility maximization. In particular, the paper presents the experimental research results concerning the test on routing metrics performance conducted in large wireless testbed with nodes controlled by utility-aware resource management subsystem referred to as CARMNET Loadable Linux Kernel Module (CARMNET LLKM) [1] based on DANUM subsystem [2]. The module is a part of CARMNET system developed by the research team realizing the Polish-Swiss Research Programme project CARMNET "CARrier-grade delay-aware resource Management for wireless multi-hop/mesh NETworks" [3] devoted to research on delay-aware wireless networking, multi-criteria routing, and the IMS (IP Multimedia Subsystem) reliable application in a wireless environment. Although the provided research on interference-aware routing is motivated by the need of optimizing the CARMNET system operation in mesh/multi-hop networks, it may be also beneficial for the research on other aspects of multi-radio multi-hop wireless networking.

The rest of the paper is structured as follows. Section II provides a discussion on related work, which contains a brief presentation of state-of-the-art interference-aware routing metrics. The introduction of the CARMNET framework is given in Section III and the proposal of a new interference-aware routing metric is presented in Section IV. Then, Section V is focused on the experimental research. It contains the description of the testbed environment, the implementation of tools necessary to conduct the tests, experimentation scenarios, results and their analysis. Finally, the paper is concluded in Section VI.

II. RELATED WORK

The presented research on routing metrics has been motivated by the need to optimize the wireless resource allocation solutions aimed at maximizing network utility. Many resource allocation systems based on the Network Utility Maximisation (NUM) model exist and determine the utility of flows according to their measured properties [1][2]. However, only a few of them have been implemented and tested in a real-world wireless mesh network [4][5]. Furthermore, the proposed approaches are not sufficient to effectively measure the utility of both delay-sensitive and throughput-oriented flows. On the other hand, the CARMNET system [1] uses a CARMNET Loadable Linux Kernel Module as a resource management subsystem based on DANUM System (DANUMS) [2], which takes both parameters into consideration. Moreover, the CARMNET system has a well-tested implementation [1], which allows researchers to focus on specific parts of the system operation.

The remaining part of this section is aimed at introducing the state-of-the-art interference-aware routing metrics used for the comparison presented in this paper. In general, the presence of interference is one of the most characteristic features of the wireless networks and a major factor constraining their performance [6]. Depending on a source of the interference, it can be categorized as controlled internal or external interference. Controlled internal interference can be reduced by the modification of the network properties (channel assignment, routing, scheduling) and can be further divided into inter-flow and intra-flow interference. Inter-flow interference may be described as a harmful competition for medium between routers when transmitting multiple flows. Intra-flow interference occurs when transmitting the single flow over a multi-hop wireless path, for which flow transmission rate is radically reduced since the medium has to be shared between each hop of a transmission. In the real-world scenario, external, uncontrolled interference in wireless systems has to be expected and should be taken into account during the routing performance analysis. Depending on a source, it can be more or less predictable and dynamic. The 802.11 networks use the Industrial, Scientific and Medical (ISM) radio bands, which are also applied in other technologies, such as Bluetooth, ZigBee or proprietary wireless audio systems.

A. Expected Transmission Count

With hop count metric proven to be ineffective in irregular WMNs topologies [7], the Expected Transmission Count (ETX) became the most popular metric for the WMN. The value of the ETX metric for a bidirectional link is calculated as it shown in the following formula:

$$ETX = \frac{1}{(1 - P_f)(1 - P_r)}, \tag{1}$$

where P_f and P_r are probabilities of the packet loss when transmitting in the forward (i.e., $node_A \rightarrow node_B$) and reverse (i.e., $node_A \leftarrow node_B$) direction, respectively.

During the implementation of the ETX metric (and each metric based on it), it is crucial to consider how a packet loss is handled by lower and upper layers (e.g., it is crucial to take into account if there is a retransmission mechanism applied).

B. Expected Transmission Time

Expected Transmission Time (ETT) is an extension of the ETX metric based on introducing a link speed factor. For each link, a value of the metric is computed according to the following formula:

$$ETT_l = ETX_l \frac{S}{B_l}, \tag{2}$$

where S represents size of the packet and B_l represents the link l data rate (as indicated by Link layer).

The ETT value can be seen as inversely proportional to so called 'goodput' of the link, representing successful packet delivery rate. The most of the implementation use only probes of the arbitrary size, which is not tied to S parameter. If all link costs are multiplied by the same constant value of S, the S parameter becomes entirely insignificant for the task of the path ordering.

C. Weighted Cumulative ETT path metric

Weighted Cumulative ETT (WCETT) [8] is built directly on the ETT metric, with the aim to achieve better performance over multi-radio links. The following formula describes the WCETT path metric for path p using K non-interfering channels [8]:

$$WCETT_p = (1 - \beta) \sum_{l \in p} ETT_l + \beta \max_{1 \leq j \leq K} X_j, \tag{3}$$

where $X_j = \sum_{l \in p^j} ETT_l$ is the attainable throughput in the single channel. The subset p^j of links on path p is defined as $p^j := \{l : l \in p \wedge channel(l) = j\}$, where function $channel(l)$ returns a channel which link l is associated with.

As it can be concluded from (3), the X_j value of the channel, which represents the bottleneck of the path (with the maximum value), is taken into account in the measure. The β value, such that $\beta \in \langle 0, 1)$ controls channel diversity. For $\beta = 0$, WCETT becomes identical to the ETT metric. Setting $\beta = 1$ is not recommended as in such a case, the metric treats longer path (in terms of the hop count) as identical as far as they use non-interfering channels.

D. Additional metrics

The performance evaluation results presented in this paper are reduced to above-mentioned metrics. However, this set may be extended by several other metrics. In particular, the Metric of Interference and Channel-switching (MIC) [9] is a metric which is based on heuristic weighting of two parts addressing the inter-flow interference impact and intra-flow interference impact, respectively. The Exclusive Expected Transmission Time (EETT) metric [10] is another interference-aware routing metric which tries to solve the problem of performance degradation in the large-scale WMNs. Finally, Interference Aware (iAWARE) metric [11] is the metric which, in the contrary to above mentioned interference-aware metrics, takes into account the physical interference model and uses signal strength of heard or sensed packets to determine Signal to Interference and Noise Ratio (SINR).

Table I summarizes the comparison of state-of-the-art routing metrics by presenting, which metrics consider particular aspects of routing in the WMN including *link loss*, *link speed*, *intra-flow interference* and *inter-flow interference*, *isotonicity*, and awareness to the *multi-radio* transmission.

Depending how the link metrics calculate the overall path cost, they could be further divided into the (i) additive metrics – the path cost is the sum of the metric value of all links, (ii) multiplicative metrics – the path cost is the product of the metric value of all links, and (iii) statistical metrics – the path cost it the minimum/maximum/average of the cost

TABLE I. FEATURES OF POPULAR WMN METRICS.

	link loss	link speed	intra-flow interf.	inter-flow interf.	isotoni-city	multi-radio
hop count	no	no	no	no	isotonic	no
ETX	yes	no	no	no	isotonic	no
ETT	yes	yes	no	no	isotonic	no
WCETT	yes	yes	yes	no	monotonic	yes
MIC	yes	yes	yes	yes	no	yes
EETT	yes	yes	yes	yes	isotonic	yes
iAWARE	yes	yes	yes	yes	no	yes

of the individual links. The metrics discussed in this paper are mostly additive (hop count, ETX, ETT), what basically is an assumption used by the majority of the routing protocols.

III. CARMNET FRAMEWORK

The assumptions and architecture of the CARMNET system have been proposed with details in [1]. The main goal of the system is to enable the WMN users to share their resources, in particular to share the Internet access. Additionally, the CARMNET vision assumes the work on integration of the delay-aware resource allocation subsystem with the Internet provider infrastructure [12]. CARMNET solutions are aimed to be integrated with public wireless networks — their have been already tested in municipal network WiFi Lugano [13] or in the socially-operated network – Malta NET – located in Poznan [14]. The Internet sharing functions (described with details in [12]) are optimized as a result of the application of the utility-aware resource allocation subsystem (i.e., the CARMNET LLKM based on Delay-Aware Network Utility Maximisation (DANUM) model [2]), which allows to compare the utility of flows with different requirements with regard to end-to-end delay and throughput.

The implementation of the CARMNET framework requires integrated studies in several research areas including wireless network resource management, multi-criteria routing, and seamless handover [15]. In this paper, we have focused on issues concerning the routing solutions supporting CARMNET resource management subsystem, i.e., DANUMS, which is responsible for resource allocation.

A. CARMNET LLKM

The CARMNET LLKM resource management subsystem (which is based on DANUM system [2]) is aimed to maximise the overall utility of a mesh network defined as:

$$\sum_{r \in S} U_r(x_r, d_r), \tag{4}$$

where S denotes a set of flows within the network; x_r – rate of flow r; d_r – delay of flow r; U_r – the utility function of flow r [2].

In order to optimise the allocation of network resources, DANUMS prioritizes flows, which gain the most utility from being served. The solution is based on “virtual queue” levels defined as a product of a packet backlog and the value of the first derivative of a given flow utility function calculated for current flow performance parameters [2]. The parameters which influence the utility value include flow’s packets delivery delay and throughput measured at destination node. Both the mentioned parameters are attained by the active measurement through the use of Delay Reporting Message (DRM) [2]. In parallel, virtual queue levels are used to perform Max-Weight Scheduling (MWS) [16] on each hop in distributed manner. The details of DANUMS implementation may be found in [1] [2].

IV. DESIGNING THE WCETTX PATH METRIC

The goal of the proposed WCETT-eXtended (WCETTX) metric is to improve the WCETT metric, which is based on ETT optimized in a way enabling simple interference-awareness for the multi-radio networks, and in consequence, to define the metric suitable to be used in CARMNET-controlled networks.

The WCETT metric assumes that by using several channels one can avoid a part of interference. Following this assumption, WCETT focuses on the maximum additive sum of ETT links’ values, grouped by the channel used. This sum represents the ‘bottleneck of the path’ and is recognized as a major contributor to its cost. Still, the authors of WCETT acknowledge that additional hops on the channels, which are not considered as a bottleneck, represent the additional cost. It is modeled by an additional sum of overall links’ ETT values, which is balanced with the major part of the metric by arbitrarily assigned constant. The setting of this constant is problematic, since one configuration cannot accommodate all of the scenarios [8]. The aim of WCETTX is to address this problem and to propose a more natural representation of the additional hops cost.

A. Formulation of WCETTX

The main improvement of WCETTX over WCETT is a clear representation of the additional hop cost of links on non-interfering channels. The assumptions made when formulating the WCETTX metric are as follows:

1) The metric of link throughput on interfering links is used in the additive manner, as transmissions on links ‘divide’ available transmission time;
2) The metric of network layer loss occurring on each hop is used as multiplicative one;
3) The channel with the maximum additive throughput metric value represents a path bottleneck and is regarded as the main factor limiting possible throughput;
4) The cost of the additional hops can be represented as the loss risk;
5) In the real-world scenario, the perfect links do not exist and a loss rate is always higher than zero, (i.e., $\underset{\text{link } l}{\forall} \; ETX_l > 1$).

The throughput link metric, such as ETT, representing ‘goodput’ of link, is commonly used as additive. Multiplicative use of the loss-based metric is not so often seen in wireless networks, as they implement a retransmission mechanism on the Link layer. However, even this mechanism fails sometimes, and loss can be seen on the higher layer in end-to-end matter, what justifies its use as the multiplicative metric. Assumption 3 is shared with the WCETT metric – each used channel is treated as not having any impact on other channels. Assumption 4 represents an optimization over WCETT aimed at differentiating between shorter and longer paths without the need for additional arbitrary assigned variables. Finally, assumption 5 is used to prevent longer (in terms of hop count) paths to be treated as equal due to the close to ideal environment and measurement inaccuracies.

Equation (5) defines the WCETTX path metric:

$$WCETTX_p = \max_{1 \leq j \leq K} X_j \times \prod_{l \in \mathrm{p}} \frac{1}{1 - netw\_layer\_loss_l}, \quad (5)$$

where K is a number of channels, $l \in \mathrm{p}$ denotes links of path p, and X_j is defined as in the case of the WCETT metric. The $netw\_layer\_loss_l$ equals to $\left(1 - \frac{1}{ETX_l}\right)^{retry}$ and is used to describe the cost of additional hops.

Probability of loss is different from Network- and Link-layer perspective, as the lower layer can retransmit the packet preventing the higher layer loss. Such a retransmission mechanism is implemented in Wi-Fi networks if no acknowledgment for the transmitted packet is received. If loss occurs, the packet is regenerated, as long as it is under $retry$ limit of retransmission attempts. This mechanism makes Network layer loss much less likely, but still possible. This end-to-end loss is applied to estimate path throughput, here represented as X_j, in the similar way like it is done in the case of the ETT metric.

B. The analysis of the WCETTX metric

The objective of this subsection is to discuss the requirements for the routing protocol necessary to apply the proposed WCETTX metric.

First, the WCETTX metric assumes that measurements of both link's loss and throughput have to be used instead of measurement of a single parameter. This approach may be regarded as an improvement over the WCETT metric, since it allows to separately model the influence of these parameters on the path cost. Additionally, it enables to take into account the association of the link to the interfering or non-interfering channel. The third parameter that must be monitored for each advertised link is a channel on which it operates. This information can be inferred by the neighboring nodes, but has to be explicitly announced during further forwarding of the topology information.

Similarly as WCETT, the WCETTX metric is non-isotonic, but monotonic. This feature has its consequences in both the routing path calculation process and routing itself. In the most common hop-by-hop routing scheme used in networks based on TCP/IP, the path is determined according to the destination node only. For non-isotonic metrics, such as WCETTX, the paths are also source dependent, thus, a more complex process for their computation is required. Moreover, the well-known algorithms used for routing path calculation, such as Dijkstra's algorithm or Bellman-Ford algorithm, process nodes in breadth-first manner and can only be applied with isotonic metrics [17]. The authors of [8] have noted that the simple adaptation of the k-shortest paths algorithm provides non-optimal routes in terms of the non-isotonic WCETT metric. The reason for that is the fact that the maximum function is used for metric calculation, what is the case also for the proposed WCETTX metric.

It has to be admitted that due to the requirement of data gathering over time as well as computational difficulty of path calculation (which slows down the time of reaction to change in the network), the WCETTX metric seems to be suited for static WMNs only. In order to use the metric in the Mobile Ad hoc Network (MANET), the ability of fast path recalculation based on a previous path should be further investigated.

It should be stressed that WCETT concentrates on intra-flow interference, while not counteracting inter-flow interference. This feature makes this metric more suitable for networks in which only several nodes exchange information between each other. Following this assumption it is worth considering to calculate WCETTX paths on-demand, only for nodes exchanging high loads of traffic, while using underlying ETT metric for fast path calculation proactively for all the nodes.

V. Experiments

The physical testbed environment has been chosen for the purposes of the proposed solution testing. While simulations offer better control over all experiment parameters as well as better scalability, these advantages are always achieved at some cost – in the simulation environment the link and physical layers of the Open System Interconnection Reference Model (OSI-RM) are often simplified, what in the case of testing interference-aware solutions could severely affect the results.

A. Testbed

The Distributed Embedded Systems Testbed (DES-Testbed) [18] has been used in the experimentation described in this paper. DES-Testbed is a non-commercial testbed designed for the purposes of research in the area of wireless mesh and sensor networks. The testbed is divided into two networks, the first one being WMN, called DES-Mesh, and the second one called DES-WSN being sensor based. Both parts are connected, as DES-Mesh consists of the core nodes, and DES-WSN is based on daughter-boards integrated with the core nodes. The whole DES-Testbed consists of over 100 core nodes, each integrated with a daughter sensor node, what makes it one of the largest academic wireless testbed. The core nodes are based on the x86 embedded PC boards, each equipped with up to three wireless network adapters. At the time of conducting the tests described in this paper only half of nodes were available for testing, since the part of DES-Testbed and the team responsible for it have moved to the University of Münster.

The DES-Testbed nodes are placed around Freie Universität Berlin (FUB) campus, thus the network topology represents a real-world scenario in which placement of nodes is irregular and external interference sources exists (e.g., generated by actively-used other networks). By default, each of the DES-Testbed nodes connects (by means of its three interfaces) to three network cells: *des-mesh0*, *des-mesh1*, and *des-mesh2*. Each of these network cells is configured to work at a separate channel, in order not to interfere with other cells. However, during experimentation we have noticed that even when using separate channels, the interference between radios may be observed. This problem is similar to the one encountered by authors of [8]. In order to mitigate the multi-radio interference issue, only one channel from of 2.4GHz band and one channel of 5Ghz band were used during experimentation. This setting corresponds to interface "wlan0" and "wlan2" of DES-Testbed nodes (des-mesh0 and des-mesh2, respectively).

Figure 1 shows the complexity of network cells *des-mesh0* and *des-mesh2*.

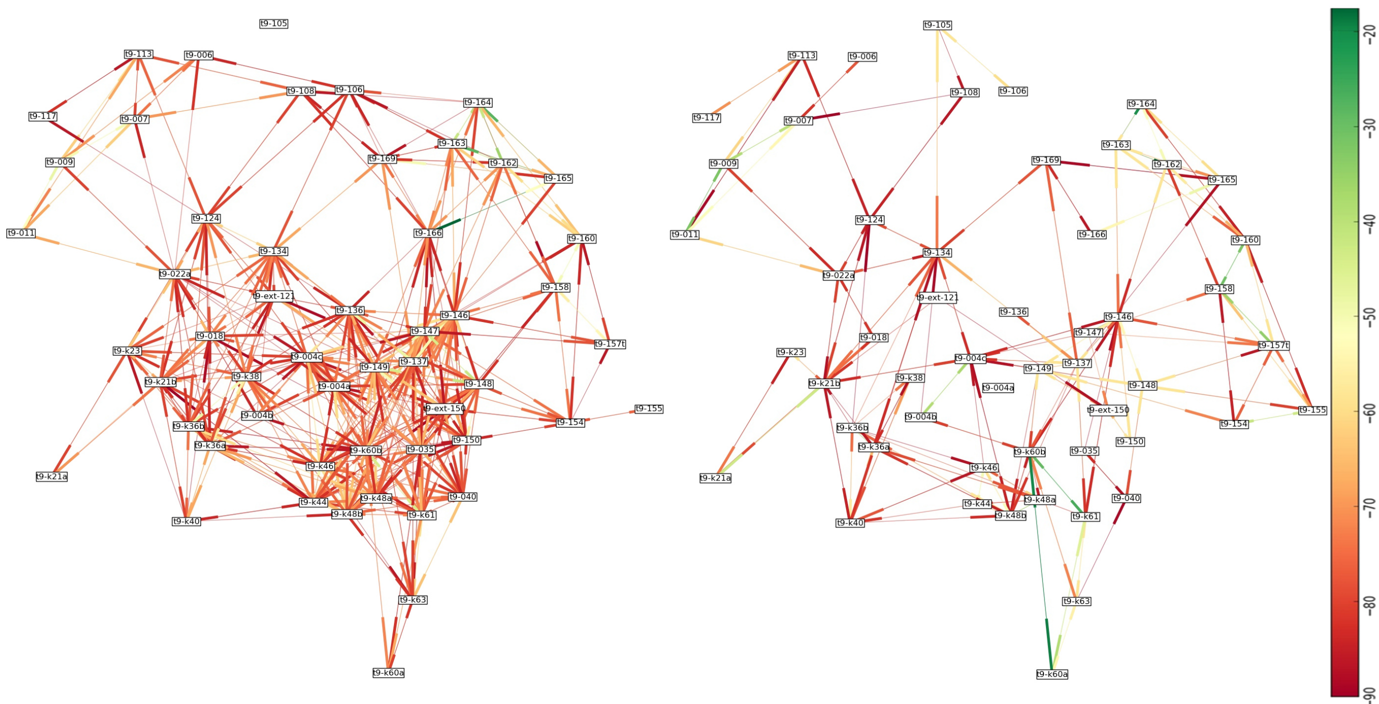

Figure 1. Overview of the signal strength in DES-Testbed network cells (from the left: *des-mesh0*, *des-mesh2*).

B. Implementation

This section contains the description of tools implemented by the authors, as well as provides the motivation for the choice of specific solutions related to technical aspects of networking in Linux, which is integral part of the testbed used.

1) Source-determined routing in Linux operating system: Although source-determined routing is required for a number of the interference-aware routing metrics, its implementation in Linux is not available. There are two ways to force the packets to travel between source and destination along a specific path in a TCP/IP network. The first one (later referred to as a Source routing IP option) is to use IP packet options Strict Source and Record Route (SSRR) or Loose Source and Record Route (LSRR) as specified by [19]. The second one (referred to as policy routing) is to make each node to choose a particular path based on both source and destination IP addresses and the set of predefined rules. Source routing IP option and source routing in the form of policy routing are easily mistaken and hard to investigate due to similarity of terminology and unpopularity of the former. The Linux kernel networking stack supports both approaches, but to a different extent. Linux user space policy routing utilities allow configuration of the routing policy rule based on a source address of the packet, which is later executed during the routing process. While in the case of the Source routing IP option, the Linux Kernel implements its handling, respecting both LSRR and SSRR headers, there are no utilities allowing insertion of such headers into the packet. Such headers could potentially be implemented with the use of the Netfilter framework or the network tunnel (TUN) virtual device, but such a solution would require introduction of additional protocol overhead and more computation as IP packet had to be created anew. The shortcomings of the source policy routing also exist, since for this approach, each possible source node has to be filtered to the separate routing table. The hard limit of the routing tables number in Linux is less than 256, which can be a problem for very large networks.

After considering all of the pros and cons, the source policy routing has been chosen in our implementation. Main factor for the decision was maturity and stability of this solution, which is important for the remote experimentation on a physical testbed, for which a recover from the potential kernel-level crash is hard to be done without a direct intervention.

2) Topology measurements and path calculation software: For the topology mapping, the basic Linux networking tools like *iw* and *iperf* have been used. The *iw* – the wireless networking configuration tool – was used to list each node neighbors detected at the Link Layer (in this case 802.11). The User Datagram Protocol (UDP) transmissions were generated by *iperf* on the source node with the maximum possible rate (as chosen by the Link layer rate adaptation mechanism) and were measured on the destination node, thus providing both packet throughput and loss rate for the interconnecting link. To ensure the reliable measurement of Link layer packet loss rate, the retry mechanism was disabled using *iwconfig* utility.

For the additional processing of the topology graph, the *Networkx* python module was used. The process of topology mapping and path calculation consisted of following steps (i) measurement gathering and generation of the network graph (ii) finding alternative paths between each pair of nodes, (iii) computing metrics for alternative paths and choosing the best path for each metric, and (iv) preparation of policy routing rules.

C. Experimentation assumptions

The experimentation follows the methodology used by authors of the WCETT metric described in [8]. The objective of the experimentation scenario was to verify intra-flow interference reduction properties of WMN routing metrics designed for multi-radio wireless communication.

The following metrics were tested: WCETTX, WCETT multi-radio metrics and the ETX metric used as a baseline comparison. In addition, for WCETT, various β values have been examined. The experiment has been run on 52 DES-Testbed nodes. The routing paths were precalculated for all of 2652 ($N * (N-1)$, where $N = 52$) source-destination pairs beforehand, as described in Subsection V-B2. From these pairs, 200 have been selected at random in order to be used as sender-receiver pairs during throughput measurement tests. The experimental evaluation presented here is limited to the tests on these randomly selected 200 pairs of source and destination nodes. The Transmission Control Protocol (TCP) connections generated by *iperf* have been used to check achievable end-to-end throughput. The Linux default "CUBIC" congestion algorithm was used, which has much more aggressive slow-start phase [20]. This feature allowed to lower the connection time down to 20 seconds when estimating the path bandwidth. To ensure that the network is clear between each test, an additional second was spent waiting after a single test to guarantee that no more packets are queued.

D. Results and analysis

Due to the hard-to-locate bug in the implementation of the 802.11 stack, in the network cell association routines, the des-mesh network cells tended to partition. In order to mitigate its effect, the presented analysis has been limited only to the source-destination pairs for which all the provided test executions have finished successfully without being influenced by the above-mentioned bug. From 200 possible samples, no less than 112 samples were gathered in each test according to this criterion.

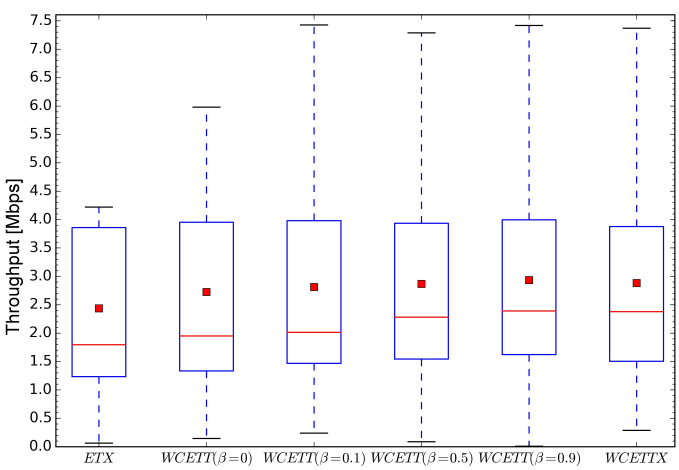

Figure 2. Two-channel scenario results obtained using *des-mesh0* and *des-mesh2* network cells.

Results of the experiment are based on 112 common samples of throughput measurements. Figure 2 is a box plot of achieved throughput. Table II repeats these results in a numerical fashion. The outliers are not shown in Figure 2, as they depict only single-hop bandwidth and are similar in every tested metrics.

TABLE II. ACHIEVED THROUGHPUT FOR EACH OF THE METRICS USING *des-mesh0* AND *des-mesh2* NETWORK CELLS.

metric	median	standard deviation	average
ETX	$1.79Mbps$	$2.26Mbps$	$2.44Mbps$
ETT	$1.95Mbps$	$2.68Mbps$	$2.73Mbps$
$WCETT(\beta = 0.1)$	$2.02Mbps$	$2.45Mbps$	$2.81Mbps$
$WCETT(\beta = 0.5)$	$2.28Mbps$	$2.37Mbps$	$2.87Mbps$
$WCETT(\beta = 0.9)$	$2.39Mbps$	$2.40Mbps$	$2.93Mbps$
$WCETTX$	$2.38Mbps$	$2.60Mbps$	$2.88Mbps$

The ETT (WCETT $\beta = 0$) metric has achieved significantly better results compared to ETX (the observed improvement of median throughput is over 18%), which is expected due to diversity of link quality. For $\beta = 0.1$ WCETT, the difference to the results of the standard ETT is not significant. For higher β values, WCETT delivers better throughput up to over 20% of improvement for median throughput when compared to basic ETT. WCETTX provides results comparable to WCETT having the β value optimized. In order to clarify the benefit from applying the proposed metric, it has to be stressed that, for a given network configuration and experiment scenario, the optimal value of β is not known in advance, and needs to be determined heuristically. The provided results confirm that in the case of WCETTX, the metric performance is equal to the maximum performance of the optimized WCETT and is obtained without the need of any parameter optimization.

It has been also noticed that even when using separate frequency bands the multi-radio interference persists. It is important to be aware that such a kind of interference may occur what may lead to the results for which the simple single-radio metrics outperform the interference-aware ones. The problem was mitigated when power of the radios was limited. The results presented here were obtained using $18dBm$ transmission strength setting.

VI. CONCLUSION AND FUTURE WORK

The main contribution of this paper is the experimental analysis of interference-aware routing metrics for multi-radio multi-hop wireless networks, which is devoted to support operation of resource management mechanisms in large-scale wireless networks. The evaluation has been performed in the DES-Testbed wireless environment using nodes operated by experimental utility-aware resource management subsystem based on CARMNET LLKM. The presented metric comparison includes the new metric proposed by the paper authors. The proposed WCETTX metric is based on the theoretical assumption of non-interference between channels of different bands and has been proven to provide the better or similar performance than other compared solutions without the heuristic optimization of parameters.

It has to be stressed that the tests in the real-world environment, while more time consuming, provide better picture of all the issues which could arise during the deployment of the solution. In particular, the tests have shown that the occurrence of multi-channel interference is possible. To the authors knowledge, no WMNs simulator implements the model which reflects performance degradation connected to the issue of the multi-radio interference.

The future work plan includes more detailed analysis of the multi-radio interference and its consideration during designing path metric. Additionally, we are going to conduct the extended experimentation using various topologies of different characteristics aimed at additional comparison of WCETT and WCETTX metric routing performance. The goal of these new experiments is the analysis of limitations of both solutions and providing the additional evidence of WCETT inaccuracy in estimation of the additional hop cost, which has been observed in results provided in [8].

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