A Comprehensive Review on Routing Metrics for Wireless Mesh Networks

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Abstract: Generally, routing protocols are very important in the field of networks, and particularly in wireless networks. Wireless Mesh Networks (WMNs) are analogous to Ad-hoc networks, therefore routing protocols for Ad-hoc networks can be implemented in WMNs. Unfortunately, these traditional routing performs poorly in WMNs because they use minimum count as routing metric. Minimum hop count metric does consider the fact that Mesh routers are equipped with multi radio interfaces which could produce interferences during the operation of WMNs. This paper presents an organized and systematic review on routing metrics for WMNs.

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1. Introduction

Wireless mesh networks (WMNs) have become very popular in the world of wireless networks especially for its low cost and its applicability [1]. This is due mainly to its autonomous capabilities (self-organizing, self-configuring and self-healing) [2, 3]. This attribute brings several advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage. Classical WMNs consist of mesh routers and mesh clients. Mesh routers generally have minimal mobility in a mesh network and form the backbone of WMNs. Mesh routers are usually equipped with a multiple radio interface to improve the capacity of the network. The mesh clients could be either stationary or mobile and can form self organized ad hoc networks which can access services by relaying requests to wireless backbone network.

Generally, routing protocols are very important in the field of networks, and particularly in wireless networks which is probably why Ramadhan and Davis [4] stated that:"*One of the important issues for wireless networks is the choice of the routing protocol as it plays an important role in managing the formation, configuration, and maintenance of the topology of the network.*". The routing protocol's strengths and weaknesses have a direct impact in the WMN's characteristics [5, 6] and WMNs are analogous to Ad-hoc networks in terms of wireless multi-hop communication [5, 7, 8]. As a result, routing protocols for Ad-hoc networks can be applied to WMNs. Initially, routing protocols used in WMNs were based on Ad-hoc networks routing protocols e.g. Ad-hoc On demand Distance Vector (AODV) and Dynamic Source Routing (DSR). These routing protocols select the best path based on the minimum hop count metric. However, due to the WMN's specific characteristics, it has been shown that the hop count metric alone does not produced the expected results in WMNs as the hop count metric does not take into consideration the link quality and the interferences. Therefore, new metrics for WMNs are critically needed [1]. More so, modeling link quality, capacity and the effect of interference can be an extremely difficult task for WMNs [9]. Consequently, based on the specific characteristics and architecture of WMNs, more realistic routing metrics and routing protocols must be proposed and used to select routes in WMNs [10] and that is why Catalan-Cid et al. [11] argued that*:"..a comprehensive solution is still needed.* " for routing metrics in WMNs.

This paper proposed a short but systematic review on existing routing metric for WMNs; with an emphasis on the disadvantages of each of them.

2. Routing metrics requirements overview

Designing routing metrics has significant impact on performance in wireless mesh networks. Based on their characteristics, WMNs does not performs well using existing solutions e.g. minimum hop count metric from both wired and wireless networks and impose unique requirements on designing routing metrics for mesh networks. Amongst these requirements are :

(i) **Route stability:** Unstable path weights can considerably reduce the performance of any network. A high number of route update messages creation is caused by constant changes. They can also disturb normal network functions as routing protocols may not congregate under frequent route updates. The stability of route costs is defined by the nature of path properties that are captured by the routing metrics, which can be either load-sensitive or topology-dependent. Load-sensitive metrics allocate a cost to a route based on the traffic load on the route.

The departure and arrival of traffics can lead to a constant change of route under load-sensitive metrics. On the other hand, topology-dependent metrics assign a cost to a route based on the topological characteristics of the route, such as the hop count and link capacity of the path. Consequently, topological-dependent metrics are usually more stable, especially for static networks where the topology does not constantly change. Topology-dependent routing metrics can be used with both on-demand and proactive routing protocols; as a result they are more desirable for mesh networks. Topology-dependent and load-sensitive metrics can be used with different routing protocols, because routing protocols have different levels of tolerance of route cost instability.

(ii) **Good performance for minimum weight paths:** For efficient mesh networks resources utilization, the minimum weight paths selected by the routing protocols should have good performance in terms of high throughput and low packet end to end delay. To accomplish this, the routing metrics must be able to take into account the characteristics of mesh networks that impact the performance of paths. These characteristics are the following[12]:

- **Paths length**: each hop generates additional delay and probably more packets drop; as a result, a longer path generally increases the end-to-end delay and decreases the overall throughput of the network. Thus, a routing metric should increase the weight of a path when the path's length increases.
- **link capacity:** Since current wireless cards are able to adapt their transmission rates based on the quality of the channel by changing their modulation schemes, the link capacity decreases when the distance between the nodes increases.
- **Packet loss ratios:** Different wireless links can have different packet loss ratios. A node might have to retransmit a packet several times on a link with a high packet loss ratio; this has an effect on both the throughput and the delay of any flow that goes through the link. For this reason, a routing metric should be able to capture the packet loss ratios to ensure good performance for the minimum weight path.
- **Interferences**: interference can be classified into two categories in WMNs; inter-flow and intra-flow interferences. Inter-flow interference refers to the interference which occurs when flows operating on the same channels are competing for the medium. So it is the interference suffered amongst concurrent flow [13]. Figure 1 shows an example of inter-flow interference between the node D and the node E. On the other hand, intra-flow interference refers to interference which takes place when adjacent nodes compete for the same channel bandwidth. In others word, it is the interference which occur when different nodes transmitting packets from the same flow interfere with one another [13]. Figure 2 shows an example of intra-flow interference between the node A and the node B on channel 1 (CH=1). So, to find minimum weight paths with good performance, routing metrics should be able to consider both intra-flow and inter-flow interferences.

(iii) **Efficient algorithms to calculate minimum weight paths:** Even though a given routing metric guarantees that its minimum weight paths have good performance, there is no guarantee that a routing protocol can have good performance if there does not exist an efficient algorithm to calculate the minimum weight paths based on the routing metric. The fundamental and adequate condition for the existence of such efficient algorithms is that the routing metrics should have a property called isotonicity. The isotonic property basically refers to the fact that a metric ought to guarantee that the order of the weights of two paths is preserved if they are appended by a similar third path.

(iv) **Loop-free outing:** Sobrinho pointed out that a metric must be isotonic to ensure that no routing loops can be formed when hop-by-hop routing is combined with Dijkstra's algorithm [12, 14]**.**

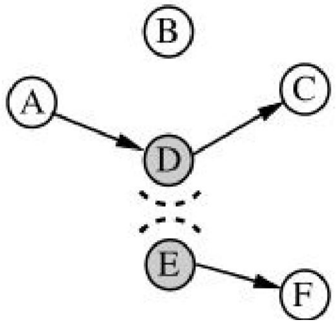

Figure 1: Inter-flow interference between two nodes

3. **Routing Metrics for Wireless Mesh Networks**

This section describes some of the routing metrics for WMNs proposed by the research community. These routing metrics are: ETX, ETT, WCETT, EPL, and MHEB.

3.1 Expected Transmission Count (ETX).

The ETX routing metric was proposed by De Couto et al. [15]. The ETX routing metric take into consideration the loss rates of the links [16] as well as the path length and the impact of the link lost ratio in selected path. ETX discovers the path with the smallest number of expected number of transmissions (including retransmissions) required for a source node to sent a packet to its destination. The metric predicts the number of retransmissions required using per-link measurements of packet loss ratios in both directions of each wireless link. The main goal of the ETX routing metric is to find paths with high throughput, in spite of losses. To achieve that goal, ETX has the following characteristics:

- ETX is based on delivery ratios, which directly have an impact on the throughput.
- ETX identifies and handles asymmetry by integrate loss ratios in each direction.
- ETX uses accurate link loss ratio measurements to make intelligent decisions for routes selection.
- ETX discourages the selection routes with more hops, which have lower throughput due to interference between different hops of the same path.
- ETX have a tendency of minimizing the spectrum use, resulting to an overall system capacity improvement.
- ETX may decrease the energy consumption per packet, as each transmission or retransmission may increase the energy consumed by a node.

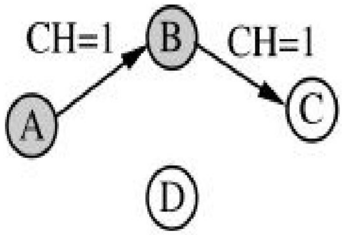

Figure 2: Inter-flow interference between two nodes

The total ETX of a route is found by adding up the ETX of each link in the route. The forward delivery ratio is the measured probability that a data packet sent by the source node has been successfully received by the destination node; the reverse delivery ratio is the measured probability that the ACK packet sent by the destination node has been successfully received by the source node. ETX selects the path by using the following equation:

$$ETX = \frac{1}{d_f \times d_r} \qquad (1)$$

Where:

- d_f is the forward delivery ratio, and
- d_r is the reverse delivery ratio.

In addition, ETX is also an isotonic metric, which guarantees easy calculation of minimum weight paths and loop-free routing under all routing protocols. However, the ETX routing metric have some shortcomings, some of these are described below:

- ETX does not consider interference [17].
- ETX does not take into account the fact that different links may have different transmission rates [1, 18].
- ETX does not consider the packets size [1]
- ETX does not specifically consider the mobility of nodes [15].
- ETX does not accurately capture the asymmetry of traffic on the wireless link [10] resulting to a poor link quality evaluation.

3.2 Expected Transmission Time (ETT).

The ETT routing metric was proposed by Draves et al. [19] in an attempt to address some of the limitations of ETX. ETT captures the effect of heterogeneity on the performance of the chosen path. It captures the multiple transmission rates at which packets are transmitted over the network. The ETT routing metric allocates lower weights to a high-bandwidth link as compared to a low-bandwidth link, as long as the loss rates on the two links are equal. Hence, ETT prioritizes fast links with minimal error rates [11]. It computes the transmission expected value in the MAC layer by reflecting link bandwidth and packet size; this that is probably why the authors in [11] define ETT as a “*bandwidth-adjusted ETX.*”. The ETT is defined as the following:

$$ETT = ETX \times \frac{PacketSize}{Bandwidth} \qquad (2)$$

This metric is also isotonic. However, the major drawback of ETT is that it does not consider the channel diversity, leading to inter-flow and intra-flow interference in the networks [20]. Another disadvantage of ETT is that it does not take into account the link quality.

3.4 Weighted Cumulative Expected Transmission Time (WCETT).

The WCETT routing metric was proposed by Drave et al. [19] in an attempt to reduce the intra-flow interference. The WCETT was designed to take into account the link bandwidth and the loss rates of links in the presence of multiple non-overlapping channels [17]. It was designed using the following assumptions [19]:

- All nodes in the network are stationary.
- Each node must be equipped with one or more IEEE 802.11 radios. These can be a combination of IEEE 802.11a, IEEE 802.11b or IEEE802.11 g radios. Each node is not required to have the same number of radios.
- If a node has multiple radios, they are tuned to different, non-interfering channels.

The three main design goals of the WCETT routing metric are as follow [19]:

- WCETT should be able take into account the bandwidth and the loss rate of a link when considering it for inclusion in a route.
- The route metric combining the cost of individual links should be increasing. That is, if a hop is added to an existing route, the cost of the route should never decrease but it should increase.
- A route build up of hops on various channels is better than a route where all the hops are on the same channel.

WCETT minimizes the intra-flow interference by allowing a sender node to optimize the entire route taken by its flow. The WCETT of the path p is defined as follows:

$$WCETT_P = (1-\beta)\sum ETT + \beta MAXX_j \qquad (3)$$

Where:

- β is a tunable parameter between $0 \leq \beta \leq 1$ which controls the preferences over path length versus channel diversity, and
- X_j represents the number of times the channel j is used on links in the end-to-end path.

The WCETT metric balanced channel diversity and path length, by varying the value of the control parameter β. It attempts to address some of shortcomings of the ETT routing metric. However, some of the weaknesses experience by WCETT is that it is not isotonic and it does not solve the problem of inter-flow interference.

3.5 Expected Link Performance

The EPL metric was proposed by Ashraf et al. [10]. EPL uses both link quality and cross-layering to gather wireless channel information in order to estimate link performance. EPL also take into account the asymmetry of traffic on the wireless link. The authors in [10] proposed to solve the problem of asymmetry by assigning a higher weight to the forward link in order to moderate the asymmetry of the packets. This is because the reverse link is meant for the ACK packets which are loss resistant and would probably be successfully received almost regardless of estimated reverse delivery ratio. The authors in [10] calculate the link delivery ratio P as follows:

$$P = \alpha d_f + (1-\alpha) d_r \qquad (4)$$

Where α is the weight assigned to the forward delivery ratio d_f and is subject to $0.5 < \alpha < 1$.

ELP is a hybrid link metric which attempts to correctly approximate of the link performance by combining link interference information along with link quality information. For optimal performance improvement of the whole networks, the main goal is to choose the routes with minimal interference.The key idea is that routes with minimal interference should be preferred to achieve global optimum. However, Equation (4) only takes into account the link quality. The authors in [10] use a cross layer mechanism to incorporate and estimate interference on the link in the metric for optimal routes selection. They define Expected Link Performance as follow:

$$\text{EPL} = \frac{1}{\alpha d_f + (1-\alpha)\, d_r} \qquad (5)$$

EPL takes into consideration the inter-flow and intra-flow interferences as well as the asymmetry of the packets to estimate the link quality. However, EPL was only evaluated in a single-radio scenario. Another drawback of EPL is that, it uses cross layering which usually lead to loss of the protocol layer abstraction. Cross layer design can can lead to a ”*spaghetti system*” which is usually difficult to maintain [21, 22].

3.6 Multi-Hop Effective Bandwidth (MHEB)

The MHEB routing metric was proposed by LI et al. [23]. MHEB provides a generic approach to calculate the achievable bandwidth along a path, taking the impacts of inter-flow and intra-flow interference and channel diversity into account. Li et al. developed an approach to compute the achievable bandwidth under intra-flow interference (ABIRF). In order to accurately capture the inter-flow interference, the authors in [23] combined the ETX metric with a newly proposed interference degree ratio to evaluate the achievable bandwidth under the inter-flow interference (ABITF). The routing metric MHEB is defined as the weighted average of ABIRF and ABITF. The Researchers in [23] evaluated the ABITF at a link i as follows:

$$ABITF_i = (1 - IDR_i) \times \frac{Bandwidth_i}{ETX_i} \qquad (6)$$

Where IDR_i is the Interference Degree Ration for a link i, $Bandwidth_i$ is the original bandwidth at a link i, and ETX_i denotes the expected transmission attempts for a successful transmission over link *i*.
Authors in [23] also computed the ABIRF as follows:

$$ABIRF = \frac{Bandwidth_x \times Bandwidth_y}{Bandwidth_x + Bandwidth_y} \qquad (7)$$

Where $Bandwidth_x$ is the maximum bandwidth for a channel x, and $Bandwidth_y$ is the maximum channel for the channel y.
Using Equations (6) and (7) the authors in [23] compute MHEB as follows:

$$MHEB = \beta \times minABITF_i + (1 - \beta) \times ABIRF \quad (8)$$

Where β is a tunable parameter and subject to $0 \leq \beta \leq 1$.

The MHEB routing metric effectively captures the effects of inter-flow and intra-flow interference, and channel diversity along a path. However, it does not guarantee optimal path selection. Authors in [23] also evaluated the performance of MHEB using fixed mesh nodes. These could cause a bias in the results as mesh client nodes in WMNs are usually mobile.

4. Conclusions

This paper presented a comprehensive review on existing popular routing metrics for Wireless Mesh Networks. ETX, ETT, WCETT, EPL, and MHEB were analytically presented. An emphasis was put on their advantages and disadvantages. From the report presented in this paper, it can be concluded. Some routing metrics such as ETX and Time ETT have been proposed in an attempt to take into consideration the link quality during the best path selection. However, these metrics still does not take into considerations the intra-flow and inter-flow interferences. WCETT, EPL and MHEB has been proposed in an attempt to address those issues; however the assumptions made during their designed was not always realistic. Therefore there is a need for "*WMNs-Specific"* routing metrics.

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