Cross Layer Optimization for Routing Based on Link Layer Delay Analysis†

Hengheng Xie, Robson De Grande, Azzedine Boukerche
PARADISE Research Lab, School of Electrical Engineering and Computer Science, University of Ottawa, Canada
E-mail: hxie072@uottawa.ca,{rdgrande,boukerch}@site.uottawa.ca

***Abstract*—The choice of a suitable path for packet transmission represents a fundamental issue to any routing protocol. The principle of choosing the shortest path is also no longer a good option for route selection since many other aspects may influence communication performance. In that sense, the link quality of the path is more important than the length of the path in a wireless network because of the unstable conditions of the channel. Expected Transmission Count (ETX) is a widely-used routing metric, which servers into the selection of the path with fewer transmissions for a successful packet delivery. However, other factors should be also considered for route selection, such as the re-transmission delay. In this paper, a comprehensive analysis on the effect of the link layer delay to the transmission throughput is presented and discussed. Given the analysis outcome, this work proposes a routing metric based on the link layer delay for IEEE 802.11. This metric allows to determine the delay of each hop along the path to evaluate the quality of the path as whole. Experimental simulation results reveal that the proposed routing metric achieves better results when compared to two other known approaches.**

I. Introduction

With the rapid development of wireless networks [1], their performance optimization becomes more important or even essential. There are some well-known mechanisms to improve the performance of wireless networks: the contention window adjustment, the hidden node detection, and the route selection. In this paper, we focus on the route selection algorithm for improving the performance of wireless networks. Our research is based on the IEEE 802.11 standard [2], which has been widely used in current wireless networks. The utilization of Wi-Fi in Vehicular Ad Hoc Network (VANET) is one of the examples of IEEE 802.11 utilization over wireless networks. The performance of the IEEE 802.11 standard is one of the critical issues of the next generation networks, which is also considered main limitation of its utilization.

Some studies [3], [4], [5], [6] have been conducted to modify the contention window range assignment algorithm of the IEEE 802.11 standard in order to optimize the performance of wireless networks. These proposed solutions aim to develop adaptation mechanisms for the contention window that enable faster reaction to sudden changes in unstable wireless channel conditions. However, interference, fading, and collision are inherent and constant factors in the environment of wireless networks and are very difficult to be predicted. Other studies on contention window adjustment [7], [8], [9], [10] have proposed a classification methodology of the services in different priority groups to optimize the network utilization; in this case, each group or class of services is assigned a specific contention window range.

On the other hand, a work [11] has been realized to propose a scheme which aims to extend the solution of the hidden node problem. The hidden node problem is commonly present in IEEE 802.11 networks, and this solution employs a detection and recovery mechanism into a joint hidden node detection through the integration of frame aggregation, block acknowledgement, and fast link adaptation.

An alternative approach to improve the wireless network performance is to devise an accurate route selection algorithm based on different metrics rather than only on the path length. The communication performance in different routes might totally differ without presenting any similarity among them. Given the inconstant channel conditions of wireless networks due to diverse unpredictable factors, the link quality tends to vary with substantial frequency. Several routing protocols for mobile ad hoc networks based on a non-hierarchical routing mechanism have been proposed previously. The most generally-known protocols are Destination-Sequenced Distance Vector (DSDV) [12], Ad hoc On-Demand Distance Vector (AODV) [13], and Dynamic Source Routing (DSR) [14]. All these protocols basically define a specific routing process which follows a determined route selection algorithm. Particularly to most of these protocols, they fundamentally adopt the shortest path algorithm for loop avoidance. However, the length of the path is no longer one of the most critical issues in wireless networking. The link quality of the path is much more significant than the length of the route since it can drastically hamper packet transmission and increase communication delay.

Expected Transmission Count (ETX) [15] is one of the several routing metrics that considers the quality of the link in some sense for route selection. ETX calculates the average number of transmissions of each path to determine its quality in terms of the over-all number of transmissions necessary to deliver a packet successfully. According to solutions based on ETX, fewer transmissions lead to small communication delays as a consequence of optimized network resource utilization. However, merely considering the number of transmissions of a given path is not enough to determine its quality: there are other factors that might also influence performance and

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throughput through delays. For instance, if a packet needs to wait a longer time to start its re-transmission, even a small number of transmissions can cause a large delay to the transmission flow. In its metric, ETX considers measurements that represent the link quality of the path by accumulating the link quality of all hops, but it ignores the composition of links altogether. Moreover, because packets are forwarded one by one according to IEEE 802.11, there is only one packet being transmitted in a given link each time. This sequential characteristic results in an accumulative delay since any additional delay in one intermediate hop causes delays in the subsequent packets.

In this work, we analyze the link layer delay in wireless networks to achieve a more accurate link quality measurement. With improved accuracy, the conditions of the link layer delay can be better determine; the link conditions in a given hop are reflected to the subsequent links and influence the whole traffic flow. These conditions are directly involved in the final throughput of the network traffic. Based on this analysis, we propose the use of a routing metric based on a cross layer link layer delay. The proposed metric measures and exams the link layer delay of each hop for route selection rather than accumulating the link quality. The link layer delay of each hop is expected to be small enough for maintaining traffic flow since any delay is most likely to cause an unrecoverable waiting times to the transmission flow.

The remainder of this paper is organized as follows. Section II presents the analysis on cross layer routing algorithms. Section III describes a link layer delay analysis from which a novel routing metric is developed to discover the best route for the service. Section IV shows the system architecture of the proposed routing metric. Section V compares through simulations the link layer delay based routing metric and AODV to emphasize the performance of our protocol. Finally, Section VI summarizes the contributions of this paper and provides some directions for future works.

II. Cross Layer Routing Metric

Most of the routing metrics traditionally only consider the number of hops, such as DSDV, AODV, and DSR, as for determining the best path for a packet to traverse. However, the number of hops in wireless networks is no longer as critical as other factors to reflect communication performance. In wired networks, the number of hops increases the probability of packet collision and bit error, and the quality of the link can be ignored in most of the scenarios since it exhibits a high quality and consequently low packet loss in most of the cases. On the other hand, since the physical layer in wireless networks is subject to several circumstances that may influence the transmission signal, the quality of the link is one of the major factors that should be taken into account for selecting the best routes.

The hope count, or number of hops, in a transmission path is still an important factor for route selection because the accumulation of the packet loss probability along the path increases when the route becomes longer. Nevertheless, the effect of the link quality heavily impacts on the throughput of a wireless transmission due to environmental elements from which a signal might be susceptible, such as interference, signal fading, and collisions. Moreover, in a layered architecture, the link quality is not immediately and directly available to the network layer protocol for the purpose of establishing a routing metric. As a result of this constraint, a cross-layer routing metric bridges between the link and network layers, facilitating the monitoring and enabling the decision-making, so this metric is proposed for improving routing in wireless networks, such as the IEEE 802.11 standard considered in the scope of this work.

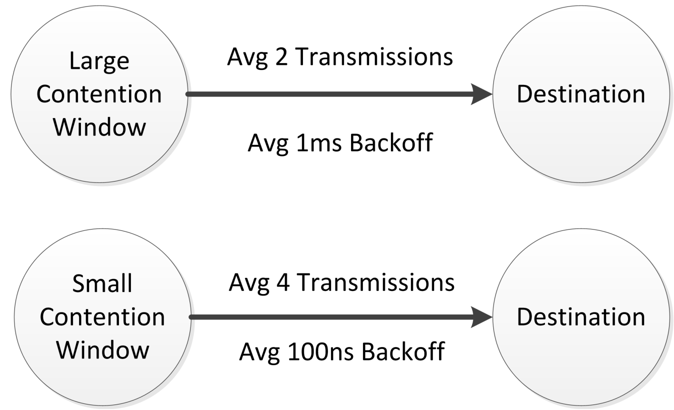

Fig. 1. Impact of the contention window to ETX.

Expected transmission count (ETX) is a cross-layer routing metric typically used to estimate the quality of a communication link. In this metric, it accumulates the packet loss probability of each hop along a path to estimate the transmission quality of the entire path. Its purpose is to provide an estimate and allow to reduce the number of transmissions for one packet delivery by choosing the route with the lowest packet loss probability. Through ETX, it is possible to choose a high quality link in the path for the transmission with the least number of transmissions. However, this metric does not provide means to guarantee the highest throughput is always achieved for a given path. Figure 1 shows an example about two one-hop routes, in which the source nodes are set to different sizes of the contention window (CW). The route with larger contention window size performs less transmissions to deliver a packet successfully; however, in this route, a longer time is required in waiting (i) before a packet is transmitted the first time if the channel is busy, or (ii) before a re-transmission is performed if a packet is lost. The route with a smaller contention window size may require an extra number of transmissions to transmit a packet successfully; on the other hand in this route, the waiting time corresponds to a shorter period for a re-transmission and for accessing the communication channel. According to ETX metric, the first path, which shows a larger contention window, is chosen rather than the second path because of its smaller number of transmissions.

In the example of Figure 1, notice that the link layer delay of the first route is higher than the link layer delay of the second one. The link layer delay can be calculated by Equation 1. The $E[delay_{LL}]$ denotes the link layer delay; $E[ReTr]$ the average number of re-transmission for a successful packet delivery; $E[BF]$ the average backoff; $E[Def]$ the average deferring time; and $E[Tr]$ the average transmission time for the last success transmission. Before each re-transmission attempt, IEEE 802.11 backs off for a certain period of time to avoid another collision. If the channel is busy while the node requests a transmission, it defers for certain time to start the request. The extra deferring time in the equation is for the last transmission, which successfully and finally transmitted the package through the link. Both $E[BF]$ and $E[Def]$ values are determined by the contention window mechanism. Equation 1 shows that the link layer delay is determined mostly by the average re-transmission time and the contention window range. Therefore, in Figure 1, the link layer delay of the first route is around 5 ms whereas the delay for the second route is around 900 ns. The second route spends less time waiting for the each re-transmission, which at the end allows it to transmit faster than the first route even though performing more transmissions. In case the sources of both routes always contain a packet to be sent, the estimated transmission interval of the first route is about 5 ms whereas of the second route is around 900 ns, which results in the second with a higher throughput. It is worth noticing that this scenario cannot be identified by the path selection algorithm using ETX as the only metric, which only considers the packet loss probability.

$$E[delay_{LL}] = E[ReTr] \times (E[BF] + E[Def]) + E[Def] + E[Tr]. \quad (1)$$

III. Link Layer Delay Analysis

As discussed in the previous section, the main factor of the transmission throughput is the link layer delay, which limits the transmission speed. In the one hop scenario, as depicted in Figure 1, each packet of the transmission flow is expected to follow certain procedure to be successfully transmitted to the next hop. On the other hand, the next incoming packet should wait in the queue until the successful delivery of the current packet to the next hop, which is the link layer delay. If this delay is too large, it affects the transmission flow by increasing the time interval between two consecutive packets, as shown in Figure 2. In the original flow of the figure, the transmission interval between two packets in sequence is smaller than the link layer delay. Therefore, packet #2 needs to wait in the queue until packet #1 is successfully transmitted; the same condition is applied to subsequent packets, such as packets #3 and #4 in the figure. The transmission flow is modified as it is affected by the link layer delay. Choosing an one-hop route with a smaller link layer instead of selecting the one-hop example in Figure 1 minimizes delays and offers more guarantees to maintain the transmission throughput along the time.

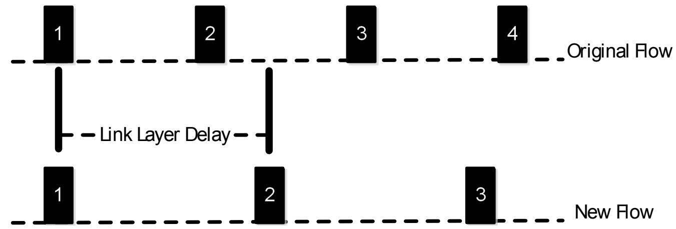

Fig. 2. Transmission flow is affected by the link layer delay

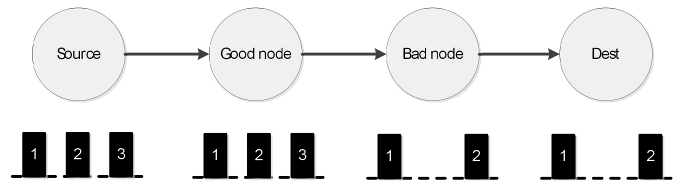

Fig. 3. Effect of link layer delay on traffic flow along the path

In a multi-hop scenario, the analysis of link layer delay is similar, deriving from the previous one-hop example. IEEE 802.11 only handles the packet forwarding along the path, and only one packet can be forwarded at a given time. Therefore, the packet is forwarded by a station along the path. If there is a slow transmission hop in a path, all the following packets are blocked deferred, as shown in Figure 3. In the figure, a good node means a node in a link layer with a small delay connection whereas a bad node means a node in a link layer with a large delay connection. A good node does not generate any negative impact on the traffic speed since the link layer delay is low. A bad node changes the transmission speed of a flow because it cumulatively delays the transmissions, working as a bottleneck in the path. The transmission flow after the bad node is totally modified, and the transmission interval of the flow is equal, or very close, to the link layer delay of the bad node. The transmission throughput cannot be recovered after the flow traverses the bad node since the bad node blocks the traffic.

Therefore, the quality of every single hop needs to be carefully considered when choosing a transmission path. Merely accumulating the link quality of each hop does not quite represent the real status of the path since the entire path delay is mostly driven by the hops with the largest delays. When defining a path selection algorithm, it is expected it ensures that the link layer delay of each hop is below certain threshold to guarantee flow throughput. In most cases, the transmission interval of a flow is roughly equal to the largest link layer delay of the path.

IV. System Architecture

The technique that employs the routing metric proposed in this paper is a cross-layer solution that measures the link layer delay of nodes and chooses the path with the smallest delay. There are two layers involved in this algorithm: the network layer and the Media Access Control (MAC) layer. The network layer handles the routing process, which corresponds to selecting and defining paths and sending out routing requests and routing replies. The MAC layer retrieves and stores the link layer delay, named as *link quality*, of all one hop neighbours, which is then accessed by the route decision in the network layer.

A. Network Layer

A basic function of the network layer is to send a *"request"* and a *"reply"*. There are two pieces of information stored in the routing request and routing reply: (i) the path in which the routing request is sent and (ii) the link layer delay of the corresponding path. The link layer delay of the path is equal to the greatest link layer delay of the link in the path and is calculated as described in Algorithm 1.

At first, the network protocol examines if there is a routing cache for a given existing route whenever a packet needs to be sent. If the destination is new to the current node, not registered in the cache, a routing *Request* is broadcasted to its neighbouring nodes. Any other node upon receiving the routing *Request* includes its information in the *Request* message and forwards the *Request* message until it reaches the sought destination. When the destination receives the routing *Request* message, it sends back a routing *Reply* message by reversing the route used to transmit the packet.

On the reverse of the route, the algorithm collects and selects the information being sent towards the origin of the request. Therefore, each node upon receiving a routing *Reply* message compares the link layer delay (*LLD*) recorded in the *Reply* message with its current *LLD* to the next hop of the path. If the *LLD* value to the next hop of the path is greater than the respective one in the *Reply* message, the current *LLD* is replaced by the received in *Reply* message. If the origin node receives a routing *Reply* message for the sent routing *Request* message, it compares the *LLD* of the routing *Reply* message to the existing route in the routing cache and stores the smallest value. If there is no previous route recorded in the cache, it stores the routing information of the *Reply* message in the cache for future incoming packets.

B. Media Access Control (MAC) Layer

The MAC protocol constantly keeps measuring the link layer delay to all one hop neighbours in order to obtain the link quality information for the routing metric. The IEEE 802.11 standard employs the messages "Request To Send" (RTS) "and Clear To Send" (CTS) to control and secure the channel from collisions on the data packets. There is also an acknowledgement message that is sent for each data packet that is successfully received in a node. The link layer delay is defined as the time interval between when a packet is available to be sent and the time its acknowledgement is received from the next hop node. Thus, the concept of Link Layer Delay is similar to the concept of Round Trip Time (RTT) of TCP since it encapsulates the whole cyclic process. Moreover, the concept of smooth RTT is adopted in this paper and is called

Algorithm 1 Routing Algorithm

Require: *Request* Routing request
Require: *Reply* Routing reply
Require: *CurPath* Current path in the cache
Require: $LLD \geq 0$ Link layer delay
Require: $CurNode \neq NULL$ Link layer delay of the current hop

```
while running do
    if receive Request then
        if Request.dst = CurNode.addr then
            Send Reply
        else
            Request.add(CurNode)
            Forward Request
        end if
    else if receive Reply then
        if Reply.dst ≠ CurNode.addr then
            Reply.LLD ← max(Reply.LLD, CurNode.LLD)
            Forward Reply
        else
            if CurPath.dst = Reply.Route.dst exist then
                if Reply.LLD ≤ CurPath.LLD then
                    CurPath ← Reply
                end if
            else
                Store Reply in the cache
            end if
        end if
    end if
end while
```

Smooth Link Layer Delay (SLLD). Based on this concern, the following Equation 2 is obtained.

$$SLLD_i \quad = \quad \alpha \times LLD + (1-\alpha) \times SLLD_{i-1}, \qquad (2)$$

where $SLLD_i$ corresponds to the *smoothed LLD* to be calculated, *LLD* denotes the current measured link layer delay, $SLLD_{i-1}$ represents the *smoothed LLD* obtained in the previous calculation and used for the smoothing, and α the smooth factor in the interval $[0, 1]$. The smooth factor is set to $1/8$ in this work; the value is obtained from experiments and is intended for avoiding sudden changes of the networks.

The MAC protocol records the time the data packet is received from the corresponding acknowledgement to calculate the *LLD*. By accumulating *LLD*, based on Equation 2, $SLLD_i$ is stored as the link quality for the route selection in the network layer.

V. Simulation Results

In this section, we evaluate our proposed routing technique through simulations using the Network Simulator 2 (NS-2) [16]. For the experiments, the protocol stack is basically based on the IEEE 802.11 protocol and the User Datagram Protocol (UDP). All the defined sources in the simulations

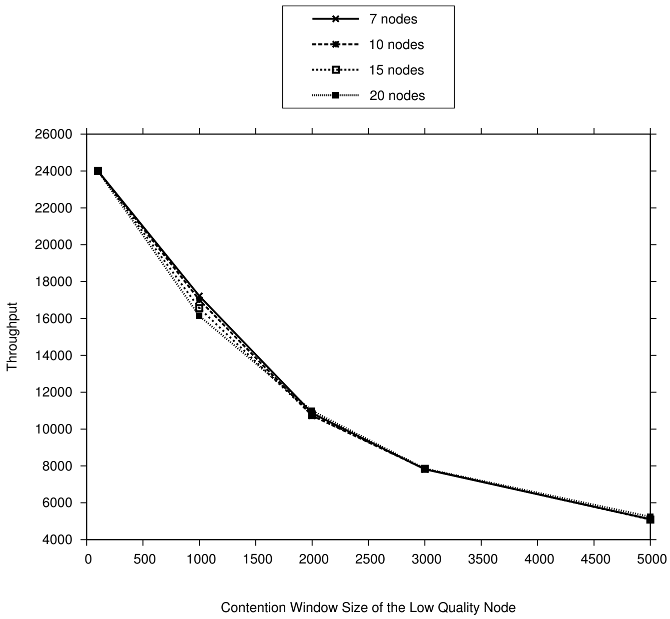

Fig. 4. Effect of the low quality link to different network sizes.

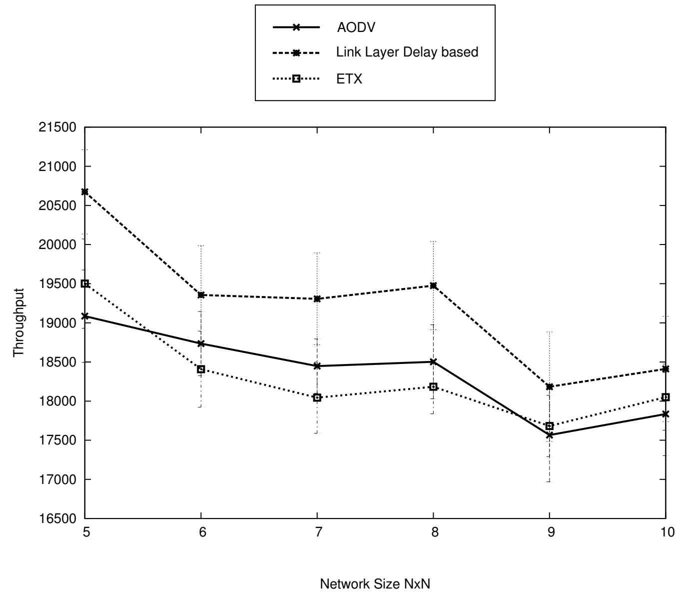

Fig. 5. The overall throughput of the network by increasing the network size.

transmit 160-byte packets following a transmission interval of 0.02 ms. Essentially, we evaluate our proposed solution using two network topologies: a chain scenario and a grid scenario. In the scenarios, the simulation experiments ranged over an increasing number of nodes and different contention window sizes. Particularly in the grid scenario, some nodes are selected and set to present low quality transmission, which are called low quality nodes. They are placed in the simulation to diversify the data links present in the environment. These low quality nodes differentiate from the rest by showing a larger link layer delay to deliver a packet; consequently, this condition forces the path throughput to be influenced by these specific nodes in case they are selected to composed a transmission flow.

We start our evaluation by simulating the chain scenario, which is more simplistic and easier to observe the difference of a low quality node generates on the transmission flow. A single low quality node is selected to integrate the path, chain. This particular node is specifically configured to present an increased contention window range, adding extra link layer delay. Figure 4 shows the simulation results considering different network sizes based on the number of chain nodes: 7, 10, 15, and 20. The goal of this simulation is to observe the extent of influence that the link layer delays exercises on the throughput of a transmission flow. As it can be seen in the results, the throughput of the transmission flow is the same or similar for all network sizes, considering the same low quality node. As discussed in Section III, the low quality node conditions the transmission flow by blocking the incoming packets, so this cumulative delay hampers the flow and causes a decrease on the throughput, which is proportional to the contention window size. As expected in the setup of this scenario, the path size is not as critical as the link quality of the node.

In the grid scenario, the proposed routing technique based on the link layer delay is compared with other two approaches: ETX and AODV. For this scenario, there are two transmission flows, and both of them contain intermediate nodes that might show high link layer delays, which are called *bad nodes*. The overall network throughput is measured in this simulation and used to evaluated the routing performance. For this grid scenario, two set of simulation experiments have been conducted. In the first set, we increase both the network size, which is the number of nodes, and the number of *bad nodes*. The number of *bad nodes* is increased proportionally to the network size, keeping the same ratio of number of nodes by *bad nodes*.

Figure 5 shows the obtained results for this first set of simulations. The proposed routing metric considering the link layer delay exhibits a higher performance than the other two routing metrics since it considers the link layer delay, which is one of the main limitations of data throughput. ETX presents a performance similar to AODV because ETX only considers the number of transmissions and ignores the average time to wait for a re-transmission. In the graph, when the network size changes from 6×6 to 8×8, the throughput shows a slight increase. This particular behaviour of the curve occurs because there are more available *good nodes* in the network for a given path length; this availability counters the delays by absorbing the effect of the *bad nodes*. The throughput is lower at a network size around 9×9 and 10×10 when compared with the network size 8×8. This happens because the path length increases the chances of the transmitted packet reaching a *bad node*. However, when comparing the results between network sizes 9×9 and 10×10, the larger size shows better throughput due to increasing the number of nodes and mostly likely keeping the same length of the path.

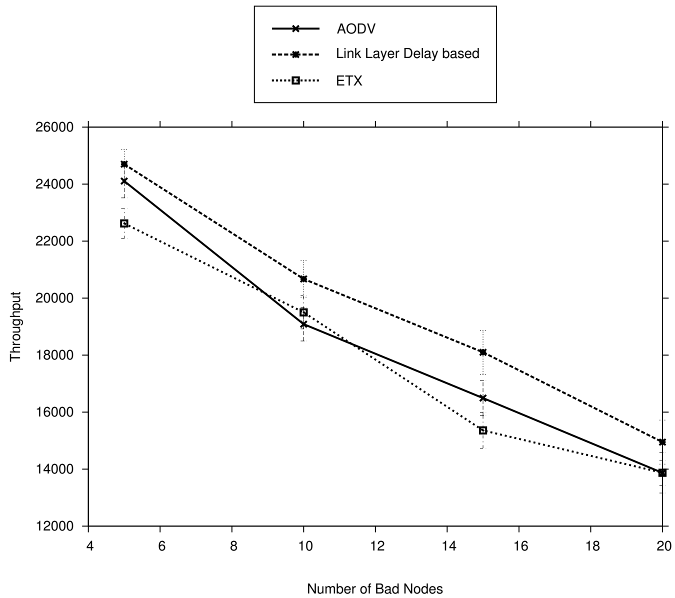

Fig. 6. The overall throughput of the network by increasing the number of low quality nodes.

In the second simulation set of the grid scenario, the network size is fixed to 5×5. However, the number of low quality nodes is increased, growing the chances of packet reaching a *bad node*. Figure 6 depicts the results obtained for this set of experiments. According to the curves in the graph, the performance of the three algorithms is very close to each other, showing a gradual decrease in the throughput as the number of a *bad nodes* increases in the network. A higher number of low quality nodes directly increases the probability of reaching a *bad node* in the transmission path. Out of that, it can be noticed in the graph that the proposed routing technique which considers the link layer delay can achieve a higher performance than the other two. As explained above, ETX fails to evidence the real factors that can affect the packet transmission and is not enough to avoid the low quality node along the path.

VI. Conclusion and Future Work

In this paper, we have proposed an approach for selecting a route based on the link layer delay. The process of properly choosing the appropriate route for a packet transmission is an important research topic in the design of routing protocols since it is directly related to the routing performance. Just selecting the shortest path for a transmission is no longer the best solution for wireless networks if data throughput needs to be ensured. The network link quality is one of the most important factors, which should be considered for the transmission performance. ETX aims to choose a path with fewer transmissions, attempting to minimize re-transmission delays and the resources the transmission consumes. The number of transmissions is one of the factors affecting the throughput; however, the time to wait for a re-transmission also needs to be considered. Therefore, the whole link layer delay of the transmissions should be considered for the performance optimization. The analysis of the effect of the link layer delay to the transmission throughput has pointed out that this particular delay greatly influences the path flow. Additionally, the performance of the proposed routing metric was simulated and compared to the performance of ETX and AODV in a grid scenario scenario. The simulation results show that the proposed metric can avoid the low quality link and achieve a performance improvement when compared to the other two approaches. As a future work, we intend to analyze the effects of the metric on throughput in more complex scenarios; we also plan to derive a more accurate link layer delay model for route selection.

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