QUIT: A Cross-Layer Routing Metric Based on Non-Utilized Outage Capacity

Bahador Amiri and Hamid R. Sadjadpour
Department of Electrical Engineering
University of California, Santa Cruz 95064
Email: {bamiri, hamid}@soe.ucsc.edu

Abstract—Routing metric design is one of the key components of routing process in wireless ad hoc networks. Several routing metrics have been proposed over the past decade considering different criteria. In this paper, we use an analytical approach to derive a practical routing metric based on non-utilized outage capacity. This IEEE 802.11 standard compliant metric which is called QUIT considers four important factors of channel, namely, Quality, Utilization, Interference and Traffic load to determine the best route. We have derived and implemented this routing metric and compared its performance with best known routing metrics for different simulation scenarios. Simulation results show that this metric outperforms other metrics for different network traffic and node mobility scenarios.

Index Terms—Routing Protocols and Metrics, Cross Layer Design, Channel Capacity, Network Traffic, Ad hoc Networks

I. INTRODUCTION

With recent introduction of IEEE 802.11n and the upcoming IEEE 802.11ac standard, Wireless Local Area Networks (WLAN) have provided exponential performance improvement through several new features. Higher bandwidth allocation, up to 40MHz for IEEE 802.11n and 160MHz for IEEE 802.11ac is allowed. Other PHY level improvements such as Multi-Input Multi-Output (MIMO) capability, transmit beamforming, Space-Time Block Coding (STBC), Short Guard Interval (SGI), Low-Density Parity Check (LDPC) coding, higher order modulation (up to 256 QAM) along with additional MAC layer improvements such as block Ack, aggregation and enhanced Request To Send/Clear To Send (RTS/CTS) mechanism are added. Higher frequency bands, over 5GHZ, are also allocated to avoid overcrowded 2.4GHz bands. These enhancements have enabled wireless LAN systems to improve reliability while increasing data rate by several folds.

In addition to above improvements, IEEE 802.11k has provided new features which can be used toward better measurement of channel quality and network traffic load. IEEE 802.11s has also introduced a mesh networking framework which has provided additional momentum toward commercialization of wireless mesh networks. Introduction of measurement features and routing framework has made IEEE 802.11 suitable for both mesh and ad hoc network implementation. These new features can be used to improve the network performance. One area which can certainly benefit from these additional features is network routing.

Network routing process can be divided into two separate steps. First, determining and assigning cost metrics to evaluate links and paths and the second step is determining the protocol for distributing routing information in the network. Several routing protocols have been proposed to address different aspects of route information distribution [1]. Most of early proposed routing protocols considered the number of hops in a route called MinHop or Hopcount metric as their cost metric. Although this metric offers simplicity and low communication delay, it tends to find paths with long and less stable links. This tendency may result in lower network capacity and reliability in wireless networks. As a result, there has been significant research on finding more efficient routing metrics to improve network performance.

In section II, we review relevant routing metrics. Most of the proposed metrics in literature do not perform well in all kinds of network configurations. The challenge has been to come up with a metric which can perform well for different topology, mobility, traffic and interference scenarios. The lack of analytically derived routing metric considering all mentioned network performance criteria that is both practical and can perform well for different scenarios has motivated us to derive the new routing metric. Our new metric, called QUIT, has two important characteristics. First, it utilizes features within IEEE 802.11 standard that makes it practical and implementable. Second, the approach takes channel utilization, link quality, interference and traffic load into consideration which results in consistent good performance for different topology, traffic and mobility scenarios.

The rest of this paper is presented as follows: Section II reviews relevant routing metrics. Section III describes the relevance of all contributing factors in our metric derivation. Section IV provides the steps toward derivation of our new routing metric. Section V shows our simulations results and compares our metric performance with some other well known approaches. Finally section VI concludes the paper.

II. RELATED WORK

Over the past decade, several routing metrics for wireless networks have been proposed [2]. One of the first quality based routing metrics is Expected Transmission Count (ETX) [3]. ETX is derived based on expected number of MAC transmissions required for a successful packet transmission. This metric is calculated based on probing statistics. Expected Transmission Time (ETT) metric [5]
enhances \textit{ETX} by integrating transmission rate and packet size. The weighted cumulative \textit{ETT} (WCETT) \cite{5} modifies \textit{ETT} to consider intra-flow interference but it does not take inter-flow interference into account.

\textit{Airtime} routing metric is the selected routing metric for IEEE 802.11s \cite{6}. This metric reflects the amount of channel resources required for transmitting a frame by considering transmit rate, frame size and frame error rate (FER). This metric does not consider traffic load or interference measurement and it may result in a congested route. IEEE 802.11s extensibility framework allows other routing metrics to be used besides \textit{Airtime} metric.

In \cite{7}, Metric of Interference and Channel-switching (MIC) is introduced. This metric improves WCETT by considering both inter-flow and intra-flow interference. MIC looks at the \textit{number} of interfering neighbors for interference calculation. In practice, interfering neighbors will cause different levels of interference depending on their proximity and traffic level. Therefore, the number of neighbors by itself is not an accurate indicator of the interference level.

In \cite{8}, interference aware routing metric (iAware) is proposed based on the physical interference model. This metric considers the effects of link loss-ratio, transmission rate as well as inter-flow and intra-flow interference by introducing an Interference Ratio (IR) factor into \textit{ETT} metric. This metric addresses the major weakness of MIC by considering the interference power level and the fraction of time each interferring source is active at the receiver.

Another group of routing metrics are based on Signal to Noise Ratio (SNR) \cite{9}–\cite{11}. SNR can be easily computed and is a very accurate measure for link quality, noise and interference but does not provide any measure of traffic load. In \cite{9}, the authors have derived an SNR-based routing metric called \textit{Inverse SNR}, to minimize overall route outage probability.

Common characteristic of all above mentioned routing metrics is that they do not consider network traffic load. Traffic load can be a significant problem for routing in IEEE 802.11 ad hoc networks because of their tendency to utilize centrally located nodes by multiple routes. Concurrent utilization of centralized nodes can cause network congestion. Further, concurrent utilization of centralized links can cause lower link capacity per route. These problems lead to higher delays and lower throughput. As a result, overall network performance degrades significantly when traffic is high. As an example, it is shown in \cite{9} while \textit{Inverse SNR} metric is capable of finding the most stable route in a single traffic flow case, its performance rapidly degrades for higher network traffic scenarios.

To resolve this problem, researchers have considered load-aware routing metrics. Load Balance Ad hoc Routing (LBAR) \cite{12} and Dynamic Load-Aware Routing (DLAR) \cite{13} both consider network traffic load to select the least loaded route. These two metrics aim to reduce the packet delay and loss ratio, however, they do not consider link quality.

Load Aware \textit{ETT} (LAETT) \cite{14} metric combines wireless access characteristics and load estimates. It considers remaining node capacities to improve \textit{ETT}. LAETT has some of \textit{ETT} drawbacks since it does not consider interference into calculation \cite{2}. WCETT Load Balancing (WCETT-LB) \cite{15} enhances WCETT by considering load balancing. The load factor is calculated based on the average queue length over transmission rate.

Two other queue based load balancing metrics are Load Aware Routing Metric (LARM) \cite{16} and Load-aware \textit{Airtime} Link Cost metric \cite{17}. The former not only captures differences in data rate, link loss ratio, intra-inter-flow interference but also traffic load. The latter metric is based on IEEE 802.11s Airtime that considers the average queue length and the number of neighbors sharing the same channel as measure of node’s traffic load.

LAETT, WCETT-LB, LARM and Load-aware \textit{Airtime} Link Cost capture both link quality and traffic load factors unlike DLAR and LBAR.

Resource Aware Routing for mEsh (RARE) \cite{18} is an isotonic metric which considers Received Signal Strength Indicator (RSSI), available bandwidth and contention level to balance link quality, availability and load. On the negative side, it uses RSSI which is not an accurate indicator for interference measurement. RSSI for low attenuation channels is mainly dominated by received signal and interference variation does not result in noticeable changes in RSSI. We address this problem in this paper by considering more deterministic indicator for interference measurement.

Exclusive Expected Transmission Time (EETT) \cite{19} and Contention Aware Transmission Time (CATT) \cite{20} metrics are also considering interference, load and link quality. Both these metrics use delay as their measurement parameter which is not very accurate \cite{2}. Interference-Load Aware (ILA) metric \cite{21} also considers both interference and network traffic load. Average traffic load of interfering neighbors, measured by their average queue length, is calculated as an estimate of the inter-flow interference. This is an improvement over metrics like MIC which only considers the \textit{number} of interfering neighbors. But queue length in general is not an accurate measure since it does not directly consider the interfering node proximity and transmission time into calculation.

Contention Window Based (CWB) metric \cite{22} includes two components of Congestion Window (CW) level and channel utilization. CW is calculated based on Frame Error Rate (FER) and channel utilization is measured based on Channel Busy Time (CBT). CBT is also used in this paper as a measure of channel utilization for our metric derivation.

Expected Link Performance (ELP) metric \cite{23} makes an improvement over ETX by considering transmission rate and interference measurement through CBT. Interference Aware Routing (IAR) metric \cite{24} considers both interference and traffic load by utilizing the MAC layer protocol for channel availability. This metric also considers the available bandwidth of the channel as a measure of transmission rate. Expected Forwarding Time (EFT) metric \cite{25} modifies \textit{ETT} metric by considering queueing delay as a measure of node’s traffic load and channel availability time as a measure of interference (similar to \cite{24}). Metric for
Interference and channel Diversity (MIND) [26] utilizes Interference Ratio (IR) concept from [8] with the addition of channel availability concept similar to [22]–[25].

We will discuss more details on channel availability and utilization in section III.

III. PERFORMANCE FACTORS

As we mentioned earlier, our new proposed metric, QUIT, considers channel utilization, quality, interference and traffic load. In this section, we explain the importance of each factor and provide a summary of how we use IEEE 802.11 standard features to identify and measure each one of them.

A. Channel Utilization

Due to shared nature of wireless medium, IEEE 802.11 standard mandates Carrier Sense Multiple Access (CSMA) MAC access protocol. With CSMA, each node has to listen to the medium by Clear Channel Assessment (CCA) mechanism for a predetermined time interval before starts transmitting. If the medium was in idle state, the node is allowed to start transmitting. If the medium was in busy state, the node has to defer transmission and wait until the medium gets back to idle state. Therefore, channel availability is inversely proportional to neighborhood’s traffic. This can be used by routing to avoid network neighborhoods with high intra-flow and inter-flow interference.

The limitations of this mechanism for interference measurement is that it treats interference in a binary fashion. This mechanism considers any energy level below its threshold as an available channel and allows transmission. But the level of interference for an idle channel can vary significantly between the receiver minimum sensitivity and the CCA triggering threshold (this can be as high as 20-30 db).

Also, this mechanism has limitation on detecting Adjacent Channel Interference (ACI) which is beyond the scope of this paper. Therefore, besides this mechanism an additional measurement is required to evaluate channel interference level when it is considered idle which will be discussed in following sections.

B. Channel Quality

Following a successful transmission, receiver will receive the data packets. At the receiver, Received Signal Strength Indicator (RSSI) can be measured as

$$RSSI_{ij} = \frac{P_i}{Attn_{ij}}, \quad (1)$$

where $RSSI_{ij}$ is the received signal strength at node $j$ when node $i$ is the transmitter, $P_i$ is the transmit power strength at node $i$ and $Attn_{ij}$ is the channel attenuation between nodes $i$ and $j$. Therefore, $RSSI$ which is proportional to inverse of channel attenuation can be used as a measure of channel quality by means of attenuation estimation. In the following section, we provide more details on this measure.

C. Interference

Signal to Interference plus Noise Ratio (SINR) from node $i$ to node $j$ can be described similar to [8] as

$$SINR_{ij} = \frac{RSSI_{ij}}{N + \sum_{k \in \eta(j) \setminus i} RSSI_{kj}}, \quad (2)$$

where $\eta(j)$ is the set of neighbors for node $j$ and $N$ is the total receiver noise power. For WLAN networks, interference varies significantly for different locations and is usually a more significant factor than noise for route selection. For the rest of this paper we use interference as a term representing both noise and interference in SINR calculation.

By combining (1) and (2), we have

$$SINR_{ij} = \frac{P_i}{N + \sum_{k \in \eta(j) \setminus i} RSSI_{kj}}, \quad (3)$$

which shows SINR provides a joint estimate of both link quality and interference. Also for simplicity purposes, we assume all nodes have the same transmit power but our approach can be extended to networks with different node transmit power. With this assumption, SINR will be mainly a function of channel attenuation and interference.

We consider joint channel utilization and SINR measurement for successful packet reception in order to incorporate link quality and interference on the selection of link for routing protocols.

D. Traffic Load

Another key factor for route selection is the traffic load at each node. As mentioned earlier, this factor is very important for IEEE 802.11 ad hoc networks because of the higher traffic for nodes that are adjacent to the access point. Several research works have been focused on network congestion problem and several routing metrics have been proposed to address this issue [12]–[26]. Some of these works address the issue of high traffic load on the neighborhood nodes while some others address the issue of high traffic load on the node itself.

We use a similar framework as LAETT metric [14] but with a different approach. We use available Airtime to consider existing traffic and calculate remaining capacity of each link. Our Airtime factor combines both traffic on the link and interfering traffic around the link. Available Airtime is measured through channel utilization which will be described in details next.

IV. METRIC DERIVATION

In this section, we first provide details on channel available Airtime calculation. Then, we show how we use Airtime as an indicator of channel utilization and combine it with SINR to find a routing metric which can maximize route Non-utilized outage capacity. As mentioned earlier, channel utilization is the indicator for availability and traffic load and SINR is the indicator for channel quality and interference.
A. Airtime Calculation

Assuming a network with single radio devices, a time unit for each node can be divided into four states:

1) Tx time: the percentage of the time unit spent to transmit current traffic load.
2) Rx time: the percentage of the time unit spent to receive current traffic load.
3) Inf time: the percentage of the time unit used by interfering traffic for which the current node is not allowed to transmit any data as explained in III-A.
4) Idle time: the percentage of the time unit which the medium is idle and not used by either current node or any interfering traffic.

During route selection process, we calculate all these time durations for each node. The time percentage when channel is in Tx, Rx or Interference state, channel is considered as utilized. Therefore, the Idle time is the non-utilized time of the channel which can be used for new traffic flow. More details on calculation of these parameters are provided in simulation section.

B. Outage Capacity

The authors in [9], [10] minimized route outage probability as the optimization criteria. In [9], it was shown that Inverse SNR routing metric outperforms other evaluated metrics assuming a single traffic flow in the network. On the other hand, since the derivation of this metric did not take channel availability and traffic load into account, performance degraded for higher network load. We address this problem by introducing new concept of non-utilized outage capacity, instead of outage probability. Since this new definition includes utilization ratio, both availability and node traffic load are considered.

As a result of fading nature of wireless channel, the received signal strength, Signal to Noise Ratio (SNR\(^1\)) and instantaneous channel capacity are random variables estimated by statistical models. One of the most commonly used models for wireless channels is Rayleigh fading model. For these channels, since SNR and capacity are random, there is a probability for channel not being able to support a required data rate due to received power fluctuations. This probability is called Outage Probability which is a metric for channel performance.

Two commonly used channel capacity definitions are Shannon (ergodic) capacity and outage capacity. For fading channels, outage capacity is considered more appropriate design criteria [27]. Assuming Channel State Information (CSI) not available at the transmitter, the transmitter will send data with fixed rate assuming a minimum SNR, \(\gamma_{\text{min}}\) [28]. Therefore, the transmit data rate is

\[
R_{\text{TX}} = B\log_2(1 + \gamma_{\text{min}}),
\]

where \(B\) is the bandwidth. The outage capacity is defined as:

\[
C_{\text{out}} = R_{\text{TX}}(1 - P_{\text{out}}) = B(1 - P_{\text{out}})\log_2(1 + \gamma_{\text{min}})
\]

Outage will happen when the received SNR, \(\gamma\), is less than \(\gamma_{\text{min}}\). For a Rayleigh fading channel, \(\gamma\) will be exponentially distributed [28]. Therefore the outage probability will be

\[
P_{\text{out}} = P(\gamma < \gamma_{\text{min}}) = 1 - e^{-\frac{\gamma_{\text{min}}}{\gamma}}.
\]

where for an SNR limited regime, outage probability decays exponentially with SNR increase and for high SNR regime, this probability asymptotically tends to zero.

By combining (5) and (6), we arrive at

\[
C_{\text{out}} = B e^{-\frac{\gamma_{\text{min}}}{\gamma}} \log_2(1 + \gamma_{\text{min}}).
\]

Considering the shared nature of wireless channel and incorporating channel utilization concept into equation 7, we introduce new concept of non-utilized Outage Capacity, \(C_{\text{NUOut}}\) between nodes \(m\) and \(n\) as

\[
C_{\text{NUOut}}^{m,n} = B(1 - U_{m,n})e^{-\frac{\gamma_{\text{min}}}{\gamma}} \log_2(1 + \gamma_{\text{min}}),
\]

where \(U_{m,n}\) is the utilization ratio for the link between nodes \(m\) and \(n\). Equation (8) shows that outage capacity is linearly proportional to both bandwidth and link availability \((1 - U_{m,n})\).

Figure 1 shows the non-utilized outage capacity versus SNR for a system with constant transmit rate, fixed \(\gamma_{\text{th}}\). It can be seen that for an SNR limited regime, \((\gamma \ll \gamma_{\text{min}})\), where the fixed transmit rate is much higher than the capability of the link, the outage capacity increases exponentially with any SNR increase. While for a high SNR regime, \((\gamma \gg \gamma_{\text{min}})\), where the fixed transmit rate is much lower than capability of the link, transmit rate is the limitations for throughput improvement. In this regime, increasing SNR will logarithmically increase the outage capacity but an improvement in channel non-utilized bandwidth, \(B(1-U)\), will linearly improve the non-utilized outage capacity. Therefore, for throughput improvement in this regime, non-utilized bandwidth is more significant than SNR.

![Outage Capacity vs. SNR (db) for SNR_{min} = 30db](image)

Figure 2 shows the outage capacity comparison for four different links versus different \(\gamma_{\text{min}}\) values. The first link has 30dB SNR and no utilization which means the link is completely available. The second link has 30dB SNR, third link has 35dB SNR and fourth link has 40dB SNR and
all three of them are 0.25 utilized. First, we observe that for the same SNR level the channel with lower utilization has a lower outage capacity proportional to $1 - U$. Second, note that the first link with lower utilization has the highest outage capacity when $\gamma_{\text{min}} \ll \gamma$. But for higher $\gamma_{\text{min}}$ values links with better SNR and higher utilization provide better performance. Therefore for a fixed $\gamma_{\text{min}}$ optimum route selection completely depends on the transmit data rate. This is a very critical concept missing in probing-based routing metrics. For these metrics, the route selected during probing may not be the best route for actual data transmission because of the differences in transmit data rate. This fact reduces the efficiency of these metrics. Third observation is that for a system with adaptive data rate, via rate adaptation schemes, the fourth link is capable of providing the highest capacity.

In summary, route selection depends on both $\gamma$ and $\gamma_{\text{min}}$. Transmit rate, bandwidth, SNR and utilization ratio are required for calculation of Non-utilized outage capacity. Non-utilized outage capacity is a joint indicator for link quality, utilization, interference and traffic which are the four components of $\text{QUIT}$ routing metric. Thus, finding the route with best $\text{QUIT}$ metric is equivalent of optimizing non-utilized outage capacity. For this approach, we select a route that maximizes the link in the route with minimum non-utilized outage capacity.

V. SIMULATION

To show the practical relevance of $\text{QUIT}$ metric, we compare our proposed metric with other well-known metrics via simulation. First, we summarize the details of our simulation environment.

A. SIMULATION ENVIRONMENT

We use Qualnet 5.0 [30] as the simulation environment for implementation and evaluation of our new route metric. IEEE 802.11 MAC protocol and 802.11g PHY model with transmit power of 15 dBm is considered. Network topology of 30 randomly distributed nodes in a $1000m \times 1000m$ square area is selected. Rayleigh fading model is considered for the wireless channel and a random speed of 1−10 m/s is selected for the mobility scenarios.

Constant-Bit-Rate (CBR) UDP traffic where 100 Mbits of data, 50000 packets of size 2048 bits, is transmitted with a rate of 500 packets/sec. For performance comparison, average packet delivery ratio and end-to-end delay are considered. For each comparison, simulation is performed over 15 different random pairs of nodes and results are averaged. Same nodes are used for all metrics. AODV routing protocol is selected as the base for implementation and comparison of all different routing metrics. For the MinHop metric basic AODV is used, while for other the routing protocol is modified to utilize specific metric.

B. SIMULATION RESULTS

The focus of our simulation is on throughput performance of different routing metrics. For comparison purposes, we have selected MinHop and ETX [3] since they are the most widely used routing metrics, Airtime metric [6] since it is the mandatory approach in IEEE 802.11s standard and Inverse SNR metric [9] because of its relevancy to our work. As mentioned above, packets are transmitted at a fixed rate and we measure the number of successfully received packets as a measure of throughput performance. Since the number of transmitted packets are fixed for all tests, number of received packets is also equivalent of delivery ratio performance.

Figure 3 demonstrates the average number of received packets for all five different metrics in a stationary network. Four different traffic load cases (1, 3, 5 and 7 traffic flows) are evaluated. As it can be seen, for 1 flow case the performance of Inverse SNR metric is similar to $\text{QUIT}$. The reason is because there is no traffic or interference in the network and both schemes utilize outage probability. But for higher traffic loads, Inverse SNR performance per flow degrades more rapidly than $\text{QUIT}$. Also, $\text{QUIT}$ outperforms all other metrics for all traffic cases.

Figure 4 shows similar comparison but for a network with mobility. It is clear that $\text{QUIT}$ still dominates all other metrics for every traffic load scenario. One reason for $\text{QUIT}$ to be able to perform much better for mobile scenario than metrics like ETX is its active measurement method. While ETX relies on passive probing, approaches with active measurement like $\text{QUIT}$ are capable of updating
during actual data transmission which is beneficial for mobile scenarios.

VI. CONCLUSION

A new concept called non-utilize outage capacity is introduced in this paper which is an indicator of the available capacity of a link considering bandwidth, SNR, channel utilization and transmit rate. Also, a new routing metric, QUIT, which considers channel Quality, Utilization, Interference and Traffic load is presented. It is shown that QUIT selects a route which optimizes the non-utilized outage capacity. Simulation results are provided to validate and demonstrate practical relevance of the new approach for IEEE 802.11. These results show that the new metric is capable of providing superior performance under different traffic and mobility scenarios.

REFERENCES


