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On Cross-layer Routing in Wireless Multi-Hop Networks

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1. Introduction

Wireless multi-hop networks represent a fundamental step in the evolution of wireless communications. Several new applications of such networks have recently emerged including community wireless networks, last-mile access for people, instant surveillance systems and back-haul service for large-scale wireless sensor networks, local high-speed P2P networking, or connectivity to rural/remote sites which was previously limited by cables.

Wireless multi-hop networks consist of computers and devices (nodes), which are connected by wireless communication channel, denoted as links. Since a wireless communication has a limited range, many pairs of node cannot communicate directly, and must forward data to each other via one or more cooperating intermediate nodes. Thus, in a unicast routing the source node transmits its packets to a neighboring node with which it can communicate directly. The neighboring node in turn transmits the packets to one of its neighbors and so on until the packets reach their final destination. Each node that forwards the packets are referred to as a hop and the set of the links, which are selected to transfer the packets, are called the route. Different routes from any nodes to any destinations are discovered by a distributed routing protocol in the network. Figure 1 shows an example of a wireless mesh network in which node S2 sends data traffic to the destination D via cooperation of intermediate nodes R1 and R2, while the other source node S1 sends out its data traffic to the gateway via the node A.

Wireless multi-hop networks are self-expanding networks; connectivity of the network is only due to existence of the nodes, thus the network can be expanded or decreased simply by adding or removing a node. In contrast, cellular networks are a much more expensive infrastructure since they need at least one base station to provide connectivity. Moreover, the capacity of the base station is limited and so not all the nodes in the coverage area can be connected to the network. Therefore, wireless multi-hop networks are a promising solution to expand the network easily as they allow flexibility and rapid deployment at low cost.

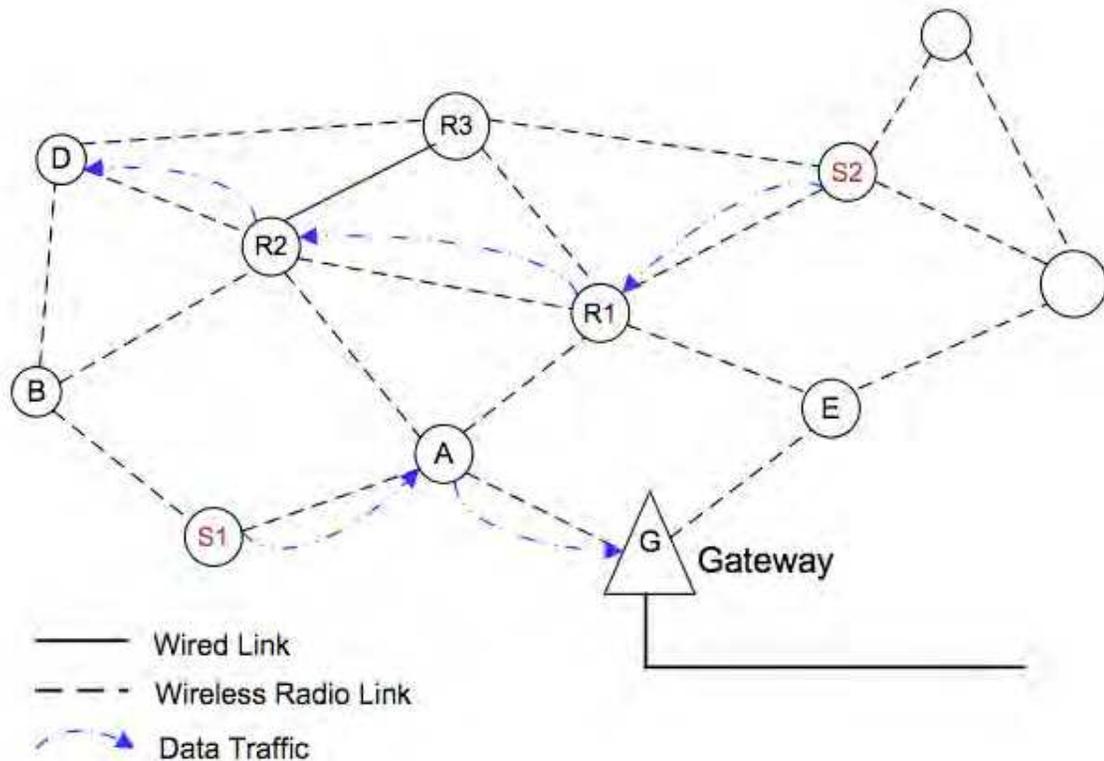


Fig. 1. An illustration of a Wireless Multi-Hop Network.

1.1 The Challenges of Wireless Multi-hop Routing in a Time Varying Environment

Routing is the fundamental issue for the multi-hop networks. A lot of routing protocols have been proposed for the wired networks and some of them have been widely used such as Routing Information Protocol (RIP) (Hedrick, 1998) and Open Shortest Path First (OSPF) (Moy, 1998). Characteristics of wireless links differ extremely from wired links. Thus, the existing routing protocols for wired networks can not work efficiently in the face of the vagaries of the radio channels and limited battery life and processing power of the devices. Moreover, the traditional routing metric of minimum-hop is not always the best solution for routing in wireless network. In the sequel, the wireless links characteristics and limitations of shortest path routing are described.

Wireless networks have intrinsic characteristics that affect intensely the performance of transport protocols. These peculiarities, which distinguish themselves from conventional wireline networks, can be summarized as follows:

- Wireless links have fundamentally low capacity. The upper band for the capacity of a wireless link follows the Shannon capacity bound.
- Signal propagation experiences large scale and small scale attenuations. Mobility of the nodes, path loss, shadowing and multi-path fading due to reflection, diffraction, scattering, absorption lead to slow and fast variations in channel quality even within the milliseconds scale (Proakis, 2004).
- The wireless medium is a broadcast medium. Therefore, in contrast to wired networks, the interference caused by other in-range traffic can unlimitedly disturb a transmission. This

causes the wireless link capacity to depend also on the sensitivity of receivers in sensing the environment as well as other links status in terms of their transmission range and power.

- Packet reception reliability over a link depends on several parameters such as modulation, source/channel coding of that link, the sensitivity of the link and the length of the packets.

Radio channels have some additional features such as asymmetrical nature and non-isotropic connectivity (Ganesan et. al, 2002; Cerpa et. al, 2003; Zhou et. al, 2004). Asymmetry of the channels means connectivity from node A to node B might differ significantly from B to A and non-isotropic connectivity means nodes geographically far away from source may get better connectivity than nodes that are geographically closer.

As a result of these characteristics, the radio cell is neither binary nor static. From the perspective of a node, the set of other nodes it can hear and the loss probability to or from these nodes vary abruptly over time with a large magnitude. This has been widely confirmed in real platforms (Couto et al, 2002; Ganesan et. al, 2002; Cerpa et. al, 2003; Couto, 2004). These random variations induce much more complexity for wireless networks to guarantee performance to transmit real-time or even critical data.

1.2 Limitations of Shortest Path Routing

Most of the existing routing algorithms use the shortest-path metric to find one or more multi-hop paths between the node pairs (Perkins & Royer, 1994; Johnson & Maltz, 1994; Park & Corson, 1997; Perkins & Belding-Royer, 2003; De Couto et. al, 2005). The advantage of this metric is its simplicity and a low overhead to the network. Once the topology is known, it is easy to find a path with a minimum number of hops between a source and a destination without additional measurement and overhead. Recent researches show that choosing the path with the smallest number of hops between nodes often leads to poor performances (De Couto et. al, 2002; De Couto et. al, 2005; Yarvis et. al, 2002).

One of the limitations of shortest path routing is that it does not capture the variable nature of wireless links. Instead, it assumes that the links between nodes either work well or do not work at all. Figure 2 shows an illustration of the different assumptions made by minimum-hop routing and link quality aware routing on the wireless links. This shows that the arbitrary choice made by minimum hop-count is not likely to select the best path among the same minimum length with widely varying qualities. Moreover, one of the current trends in wireless communication is to enable devices to operate using many different transmission rates to deal with changes in connectivity due to mobility and interference. In multi-rate wireless networks, minimum-hop works even worse. Selecting the minimum-hop paths leads to maximizing the distance travelled by each hop, but longer links are not robust enough to operate at the higher rates. Therefore, shortest path routing results in selecting the paths with the lowest rates, which degrades dramatically the overall throughput of the network.

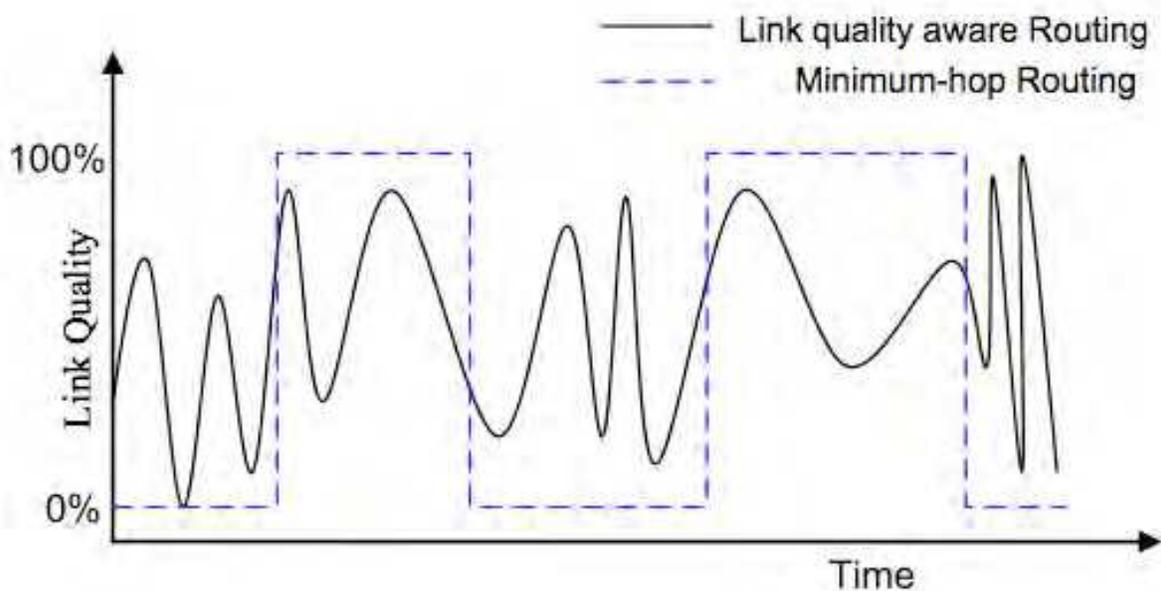


Fig. 2. Different assumptions for wireless link connectivity made by minimum-hop routing and link quality aware routing.

Furthermore, transmitting the flow over the low-rate links degrades the performance of other flows, which are transmitted over higher rate links. The main reason of this effect is that slow-speed links require larger amount of medium time to transmit a packet over the shared wireless medium and so block the other flows for a longer time. Heusse et al. denotes this problem as Performance Anomaly of 802.11b (Heusse et. al, 2003). They show analytically that a contending node with lower nominal bit rate degrades the throughput of faster contenders to even a lower bit-rate than the slowest sender. (Mahtre et. al, 2007; Razafindralambo et. al, 2008; Choi et. al, 2005) have evaluated and shown the same effect.

Another effect of multi-rate option for a minimum hop routing is that in multi-rate networks broadcast packets benefit from the longer range of low rate transmissions to reach farther nodes and so are always sent at the lowest transmission rate. Therefore, hearing the broadcast Hello messages from a node is not a good enough basis for determining that two nodes are well connected for transferring data packets at high rates. Lundgren et al. have referred to this effect as the gray-zone area (Lundgren et. al, 2002). A gray zone is the maximum area, which is covered by the broadcast messages at low rate, but not all the nodes in this area can forward the packets at high rates.

Choosing closer nodes with shorter-range links instead of minimum-hop routes can solve this problem. Consequently, minimum-hop metric has no flexibility in dealing with random quality fluctuations of the links. Link quality aware routing counters these limitations by using observation of miscellaneous parameters such as frame delivery or signal strength to select the good paths. In this approach, link quality metric is measured and observed in order to predict the near future quality of the links. This estimation is then used to determine the best route.

1.3 Cross Layer Interaction as a Solution

Typically, Open System Interconnection protocol stack (OSI) is divided into several layers which are designed independently. The interactions between adjacent layers are defined by some specific interfaces. Recently, in the quest of finding a link quality aware routing for wireless multi-hop networks, numerous link quality aware metrics have been proposed, which most of them are based on cross layer interactions between various layers of the protocol stack. Lately, there are many research efforts which show that transferring the status information between the layers can lead to a great improvement in network performance (Conti et. al, 2004; Shakkottai et. al, 2003; Goldsmith & Wicker, 1998). Recent activities of IEEE 802.11 task group in mesh networking have released IEEE 802.11s. It extends the IEEE 802.11 Medium Access Control (MAC) standard by defining an architecture and protocol that support both broadcast/multicast and unicast delivery using radio-aware metrics over self-configuring multi-hop topologies. This evolution pushes employing the cross layering technique in the real platforms in near future.

This chapter argues that the cross layering technique can be a promising solution in providing flexibility to the wireless network changes. Nevertheless evaluating the benefits of cross layer routing is often only based on the throughput, which is simplistic. Current studies generally do not consider the impact of other criteria such as response time or route flapping, which influence greatly applications performances in terms of throughput, but also mean delay, jitter and packet loss.

In the next section, a state-of-the-art of the main cross-layering metrics that have been proposed in the literature are presented. Then, the concept of reactivity for a link quality aware routing as a mean to analyse the true benefits of the cross-layer routing is introduced. Section 4 concludes this chapter.

2. Link Quality Aware Routing

Most of the primitive works in routing protocols for wireless multi-hop networks are inherited from existing routing protocols in wired networks. They devise mostly on coping with changing topology and mobile nodes (Perkins & Bhagwa, 1994; Perkins & Royer, 1999; Johnson & Maltz, 1994) and traditionally find the possible routes to any destination in the network with the minimum hop-count. As explained in Section 1.2, shortest path routing has sub-optimal performance, as they tend to include wireless links between distant nodes (De Couto et. al, 2002). A multitude of quality aware metrics have been proposed in the last decade which deal with the strict bandwidth and variable quality of wireless links and try to overcome the disadvantages of the minimum hop (MH) routing. Although most of them have been designed with the objective of increasing the transport capacity, each of them considers different QoS demands such as overall throughput, end-to-end delay, etc. Therefore, the proposed approaches for link quality aware routing can be categorized according to the aim of their design.

2.1 Wireless Network Capacity

The main purpose of efficient routing in mesh networks is improving the achieved capacity. The notion of capacity for wireless ad hoc network was defined as the maximum obtainable throughput from the network. It was first introduced by Gupta and Kumar in their seminal work (Gupta & Kumar, 2000). Network capacity for wireless multi-hop networks is

generally unknown, except for some centralized scheduling-based MAC protocols like Time Division Multiple Access (TDMA) where the problem finds a mathematical formulation.

The main finding in (Gupta, 2000) is that per-node capacity of a random wireless network with n static nodes scales as $\Theta\left(\frac{1}{n \log n}\right)$. They assume a threshold-based link layer model in

which a packet transmission is successful if the received SNR at the receiver is greater than a fixed threshold. Instead of this ideal link layer model, Mhatre et al. consider a probabilistic lossy link model and show that the per-node throughput scales as only $\Theta\left(\frac{1}{n}\right)$ instead of

$\Theta\left(\frac{1}{n \log n}\right)$ (Mahtre & Rosenberg, 2006).

These asymptotic bounds are calculated under assumptions such as node homogeneity and random communication patterns. Therefore, some researches try to relax some of these assumptions on network configuration. Jain et al. focus on interference status among the transmitters as one of the main limiting factors on routing performance (Jain et. al, 2003). They propose to represent interference among wireless links using a conflict graph. A conflict graph shows, which wireless links interfere with each other, such that each edge in the connectivity graph is represented by a vertex and there exists an edge between two vertices if the links interfere with each other. Thus, the throughput optimization problem is posed as a linear programming problem in which upper and lower bounds of the maximum throughput are obtained by finding the maximal clique and independent set in the conflict graph.

Karnik et al. extend the conflict graph idea to a conflict set (Karnik et. al, 2007). Their rationale is that an interference model can not be binary since for a given link, generally there is a subset of links that at least one of them should be silent when the given link is transmitting. They propose a joint optimization of routing, scheduling and physical layer parameters to achieve the highest throughput. Both these proposals bring valuable achievement but as they investigate the highest capacity of a network, they have to assume TDMA instead of contention-based algorithm, which leads to probabilistic results. Hence, they implicitly assume that data transmissions are scheduled by a central entity. Therefore they may not be applied easily to more practical networks such as IEEE 802.11 with random access to the channel.

Computing the optimal throughput, despite of giving a good vision to the maximum achievable throughput in the network, may not be implementable in a real network. There are many complicated issues such as necessity of having a distributed routing/scheduling protocol, random quality for the wireless links, limited allowable overhead to the network, compatibility with MAC 802.11, etc., that motivate the researchers to find a practical solution to achieve a good performance.

2.2 Maximum Throughput Routing

Most of the work done in this area relies on the broadcasting of extra probe packets to estimate the channel quality (ex. Sivakumar et. al, 1999; De Couto et. al, 2005; Draves & Zill, 2004). However, since the quality of the wireless links depends significantly on physical settings (such as transmit rate and packet size), the probes may not reflect the actual quality of the links. The reason is that for preventing to throttle the entire channel capacity they

have to use small-sized probes at low transmission rate. Therefore the quality experienced by larger data packets at variable transmission rate is not the same as probe packets.

De Couto et al proposes a simple and effective routing metric called the expected transmission count (ETX) for 802.11-based radios employing link-layer retransmissions to recover frame losses (De Couto et. al, 2005). ETX of a wireless link is defined as the average number of transmissions necessary to transfer a packet successfully over a link. For estimating the expected number of transmission of the links, each node broadcasts periodically fixed-size probe packets. This enables every node to estimate the frame loss ratio p_f to each of its neighbors over a window time, and obtain an estimate p_r of the reverse direction from its neighbors. Then, assuming uniform distribution of error-rate over each link, the node can estimate the expected transmission count as $\frac{1}{(1 - p_f)(1 - p_r)}$. The ETX of

a path is obtained by summing up the ETX of its links. Therefore, each node picks the path that has the smallest ETX value from a set of choices. ETX has several drawbacks. First, its measurement scheme by using identical small-sized probe packets does not reflect the actual error-rate that the data packets experience over each link. The accuracy of the measurement scheme of a link quality metric has a great impact on its functionality (Karbaschi et al. 2008). Furthermore, ETX does not account the link layer abandon after a certain threshold of retransmissions. This may induce to select a path, which contains links with high loss rate. Koksai et al. introduce another version of ETX, called ENT (Effective Number of Transmissions), which deals with this problem (Koksai & Balakrishnan, 2006). ENT takes into account the probability that the number of transmissions exceeds a certain threshold and then calculates the effective transmission count based on an application requirement parameter, which limits this probability. Moreover, ETX by taking an inversion from the delivery rate to get the expected number of transmissions implicitly assumes uniform distribution for the bit error rate (BER) of the channel, which may not be correct.

The Expected Transmission Time (ETT), proposed by Draves et al. improves ETX by considering differences in link transmission rates and data packet sizes (Draves & Zill, 2004). The ETT of a link l is defined as the expected MAC layer latency to transfer successfully a packet over link l . The relation between ETT and ETX of a link l is expressed as:

$$ETT_l = ETX \frac{s_l}{r_l} \quad (1)$$

where r_l is the transmission rate of link l and s_l is the data packet size transmitted over that link. The weight of a path is simply the summation of the ETT's of the links of that path. The drawback of ETT is, as it is based on ETX, it may choose the paths, which contain the links with high loss rates. (Draves & Zill, 2004) proposes also another new metric based on ETT, which is called Weighted Cumulative Expected Transmission Time (WCETT). The purpose of this metric is finding the minimum weight path in a multi-radio network. The WCETT is motivated by observing that, enabling the nodes with multi-radio capability reduces the intra-flow interference. This interference is caused by the nodes of a path of a given flow competing with each other for channel bandwidth. For a path p , WCETT is defined as:

$$WCETT(p) = (1 - \beta) \cdot \sum_{l \in p} ETT_l + \beta \cdot \text{Max}_{1 \leq j \leq k} (X_j) \quad (2)$$

where X_j is the number of times channel j is used along path p and β is an adjustable parameter for the moving average subject to $0 \leq \beta \leq 1$. (Yang et. al, 2005) shows that WCETT is not non-isotonic and thus it is not a loop-free metric.

One of the characteristics of wireless links that can be observed is the received signal strength. It is very attractive if link quality can be reliably inferred by simply measuring the received signal strength from each received packet. Theoretically, the BER is expected to have a direct correlation with the received signal-to-noise ratio (SNR) of the packet, and the packet error rate is a function of the BER and coding. Therefore, the SNR level of the received packets has been widely used as a predictor for the loss rate of the wireless links (ex. Goff et. al, 2001; Dube et. al, 1997). (Aguayo et. al, 2004; Woo, 2004) through collecting experimental data have shown that although SNR has an impact on the delivery probability, lower values of SNR has a weak correlation with the loss rate of the links. Thus, it can not predict the quality of the links easily. In addition, (Woo, 2004) illustrates that where traffic load interference happens, collisions can affect link quality even though the received signal is very strong. The main reason is that prediction of the link quality by observing the SNR samples of the packets, counts only on the packets which are received successfully. This leads to ignoring the congestion status of the links.

A number of proposed wireless routing algorithms collect per-link signal strength information and apply a threshold to avoid links with high loss ratios (Goff et. al, 2001; Yarvis et. al, 2002). In the case that there is only one lossy route to the destination, this approach may eliminate links that are necessary to maintain the network connectivity.

2.3 Minimum Delay Routing

Some existing link quality metrics focus on finding the best paths based on the end-to-end delay associated to each path. The rationale for minimizing the paths latency is that in a fixed transmission power scenario, packets latency for reaching successfully to the other end of a link can provide an estimation of the quality of that link. The average round trip time (RTT) of the packets over each link is one of the delay based parameters representing the link quality. (Adya et. al, 2004) for instance proposes this metric. To calculate RTT, a node sends periodically a probe packet carrying its time stamp to each of its neighbors. Each neighbor immediately responds to the received probe with a probe acknowledgment which echoes its time stamp. This enables the sending node to calculate the RTT to each of its neighbors. Each node keeps an average of the measured RTT to each of its neighbors. If a probe or a response probe is lost, the average is increased to reflect this loss. A path with the least sum of RTTs is selected between any node pair.

The RTT reflects several factors, which have impact on the quality of a link. First, if a link between the nodes is lossy its average RTT is increased to give a higher weight to that link. Second, either if the sender or the neighbor is busy, the probe or its response is delayed due to queuing delay which leads to higher RTT. Third, if other nodes in the transmission range of the sender are busy, the probes experience higher delay to access the channel again resulting in higher RTT. Concisely, RTT measures the contention status and error rate of a link.

However, the small probe packets in comparison to larger data packets are rarely dropped over a lossy channel. This hides the actual bandwidth of the links. Moreover, (Draves et. al, 2004) shows that RTT can be very load-sensitive which leads to unnecessary route

instability. Load-dependency of a metric is a well-known problem in wired networks (Khanna & Zinky, 1989). To suppress the queuing delay in the RTT, Keshav, 91, proposed the packet-pair technique to measure delay of a link. In this approach to calculate the per-hop delay, a node sends periodically two probe packets back to back to each of its neighbors such that the first probe is small and the next one is large. The neighbor upon receiving the probes calculates the delay between them and then reports this delay back to the sender. The sender keeps an average from the delay samples of each neighbor and paths with lower cumulated delay are selected. This technique, by using larger packet for the second probe, reflects more accurately the actual bandwidth of the links, although it has higher overhead than RTT. Draves et. al, 2004 discusses again that packet-pair measurement is not completely free of self interference between the neighbors, although less severe than RTT. Awerbuch et. al 2004 proposes the Medium Time Metric (MTM) which assigns a weight to each link proportional to the amount of medium time consumed by transmitting a packet on the link. It takes the inverse of the nominal rate of the links to estimate the medium time. The variable rate of the links is determined by an auto-rate algorithm employed by the networks, such as ARF or RBAR. Existing shortest path protocols will then discover the path that minimizes the total transmission time. This metric only handles the transmission rate of the links and does not account the medium access contention and retransmission of packets at the MAC layer. Zhao et al. 2005 introduces a cross layer metric called PARMA, which aims to minimize end-to-end delay which includes the transmission delay, access delay and the queuing delay.

They consider a low saturated system with ignorable queuing delay. A passive estimation is used for the channel access delay and the transmission delay on each link is calculated as the ratio of packet length to the link speed. This metric has a good insight into estimating the total delay of each link but has simplified very much the problem of the delay calculation. For instance, it assumes that the links are error free and no packet retransmissions occur over them.

2.4 Load Balancing

In order to make routing efficiently and increase network utilization, some researchers have proposed congestion aware routing with the aim of load balancing in the network. One of the methods for spreading the traffic is using multiple non-overlapping channels. Kyasanur & Vaidya, 2006 propose a Multi-Channel Routing protocol (MCR) with the assumption that the number of interfaces per node is smaller than the number of channels. The purpose of their protocol is choosing paths with channel diversity in order to reduce the self interference between the node pairs. Moreover, they take into account the cost of interface switching latency. MCR is based on on-demand routing in a multi-channel network. While the on-demand route discovery provides strong resistance to mobility-caused link breaks, the long expected lifetimes of links in mesh networks make on-demand route discovery redundant and expensive in terms of control message overhead. Therefore, this protocol is not totally appropriate for mesh networks. Yang et al. focus more on mesh networks and propose another path weight function called Metric of Interference and Channel-switching (MIC). A routing scheme, called Load and Interference Balanced Routing Algorithm (LIBRA) is also presented to provide load balancing (Yang, 2005). MIC includes both interference and channel switching cost.

2.5 Routing with Controlling Transmission Power

Numerous works in efficient routing in multi-hop networks has focused on power control routing. The problem of power control has been investigated in two main research directions: energy-aware and interference-aware routing. In energy-aware routing approaches the objective is to find power values and routing strategy, which minimizes the consumption of power in order to maximize the battery lifetime of mobile devices. Therefore these works are suitable for sensor and ad hoc networks as in wireless mesh networks power is not a restricted constraint. Power control in interference-aware routing aims to find the optimal transmission power which gives the higher throughput or the lowest end-to-end delay. Therefore, transmission power of the nodes is controlled in order to reduce interference while preserving the connectivity. There are a lot of researches in this area. For instance Iannone et al. propose Mesh Routing Strategy (MRS) in which transmission rate, PER and interference of each link are taken into account (Iannone & Fdida, 2006). The interference is calculated based on the transmission power and number of reachable neighbors with that power level. The disadvantage of their approach is that they do not consider that links with different transmission rate have different sensibility for being disturbed by the neighbors' transmission. This effect has been taken into account in (Karnik et. al., 2008) where the authors propose a network configuration to have an optimal throughput.

The foreseen alternatives to minimum hop metric consist in establishing high quality paths, by tracking various link quality metrics in order to significantly improve the routing performances. Thus, the challenge lies in selecting *good* paths, based on a *relevant* link quality metric. However, the stability issue of link quality aware routing which can be extremely important specially in providing quality of service for jitter sensitive applications has not been addressed by the existing research efforts. In the next section, a quantitative tool to investigate the routing reactivity and its impact on applications performances is introduced.

3. Reactivity of Link Quality Aware Routing

A more reactive routing responds faster to link quality changes. This leads to detect the lossy channel faster and so, to converge to the higher quality path in a shorter time. Meanwhile, fast reacting to channel variations may produce higher path flapping and consequently higher jitter level. Therefore, there is a trade-off between providing ensured stability in selecting the paths and obtaining a high possible throughput from the network. The frequency of link quality changes may be very different for distinct wireless links (due to some factors such as fast or slow fading, nodes mobility, etc.) (Koskal & Balakrishnan, 2006; Aguayo et. al, 2004). In order to track as much as possible all the link changes and always choose a high quality path, the routing should respond accurately and as fast as possible to these changes. Response time refers to the time required by the routing agent to take into account the new link quality status.

The reactivity of the routing depends on the updating frequency of the routing tables and the sensitivity degree of the routing metric to channel variations. The updating frequency of the routing tables defines the rate at which the shortest paths are recalculated based on the current value of the link quality metrics. Although the updating period of the routing is generally longer than the time-scale of link quality variations, a shorter update period is able

to respond faster to link breakage or quality degradation and in turn will lead to a higher throughput. However, frequent changes of the selected route induce packet reordering and jitter issues. Moreover, reducing the updating period of the metric obviously produces a higher amount of routing overhead. This may overload the network and could severely degrade the network performance. The sensitivity degree of the routing metric to link quality variations is the other parameter which obviously has a great impact on the routing response time. The sensitivity degree depends on the way the set of measured parameters (frame loss, delay, SNR, ...) are mapped onto the metric. Sensitivity degree S of a link quality metric is defined as the norm of the gradient of the defined metric function with respect to the set of parameters that measures the link quality. Let q be the set of measured parameters and $m(q)$ the calculated metric based on q . The sensitivity of the metric is:

$$S_m(q) = \left\| \vec{\Delta} m(q) \right\| \quad (3)$$

With a highly sensitive metric, the variations of link conditions are intensified. The path metric, which aggregates the link metrics along a path, fluctuates faster and the probability of changing the selected route increases. The possibly resulting route flapping may cause higher jitter which for some applications is harmful as reordered or delayed packets may be considered as lost ones. This section focuses on investigating the impact of a more sensitive metric on route flapping, control overhead and real-time application performances.

3.1 Impact of the Sensitivity of a Link Quality Metric

In (Karbashi et. al, 2008) it is shown that measurement scheme and obviously the relevance of the measured parameters have a great impact on the measurement accuracy and thus on the final result. Numerous link quality routing have been proposed in the last decade. However, in order to compare the impact of the sensitivity of two link quality metrics on the routing performance, their measurement scheme and the parameters they measure for estimating the quality of the links should be the same. No such two link quality metrics with identical observed parameters and measurement scheme can be found in the literature. Therefore, to conduct the study, two comparable and realistic link quality metrics are introduced in the following.

ARQ mechanism in 802.11b with retransmission of frames over lossy channels wastes bandwidth and causes higher end-to-end delay and interference to the other existing traffics. Therefore, the number of frame retransmissions at the MAC layer has been widely used as an estimator of the link quality (De Couto et. al, 2005; Koskal & Balakrishnan, 2006; Karbashi et. al, 2008). Therefore, this section presents two comparable link quality metrics based on this retransmissions number.

The first link quality metric, called m_1 , is based on the FTE metric introduced in (Karbashi et. al. 2005). Assuming that RTS/CTS is enabled for solving the hidden terminal problem, the quality and interference status of the adjacent links of a sender can be estimated by measuring the average number of required retransmissions of data and RTS frames at the MAC layer to transfer a unicast packet across a link. Therefore, each node measures the m_1 by keeping the retransmissions count of RTS and data frames over the neighbor links as follows.

Let $k_{xy}(i)$ - respectively $l_{xy}(i)$ - be the number of transmissions (including retransmissions) of the i^{th} data packet - respectively i^{th} RTS packet - over the x to y link. Thus the set of measured parameters (q) over this link will be defined as $q_{xy}(i) = \{k_{xy}(i), l_{xy}(i)\}$. The success rate in delivering two frames of data and RTS from x to y denoted by $m_1(q_{xy}^i)$ is computed as:

$$m_1(q_{xy}^i) = \frac{2}{k_{xy}(i) + l_{xy}(i)} \quad (4)$$

Referring to Equation 4, increasing the number of retransmissions of RTS or data frames reduces the value of m_1 and for a perfectly efficient link $m_1(q_{xy}^i)$ is equal to unity. If the number of retransmissions reaches a predefined threshold, the sender gives up sending the frame. In this case, $m_1(q_{xy}^i)$ is set to zero which degrades the overall average link quality very much. m_1 can be interpreted as an estimation of the success rate of transmissions over a link. Another metric, called m_2 is defined based on the same measured parameters. Assuming that the failure in transmission of data and RTS frames are independent from each other, the success rate of transmission over the link x to y can be calculated by multiplying the success probability of sending RTS and data frames as follows:

$$m_2(q_{xy}^i) = \frac{1}{k_{xy}(i)} \times \frac{1}{l_{xy}(i)} \quad (5)$$

With the same argument, if the sender gives up sending RTS or data frames, $m_2(q_{xy}^i)$ is set to zero.

Figure 3 illustrates the calculated success rate returned by m_1 and m_2 as a function of the number of data and RTS retransmissions for each sent packet over a given link (Equation 4 and 5). As shown in this figure, an interesting property of both m_1 and m_2 is that their variations over the range of RTS and data retransmission numbers is not uniform. Indeed, both metrics are much more sensitive to a given variation of its arguments k_{xy} and l_{xy} when these parameters ranges between 1 and 4 than for values ranging between 6 to 10. In other words, the quality variations of a poor link are far less reflected in the metric than the variations of a high quality link. This is desirable since if a link does not work well and there is no alternate much higher quality link, it is not worth changing the selected path. In counterparts, quality variations of a good links have a much greater impact on the throughput of that link. As a result, good quality links should be more prone to changes.

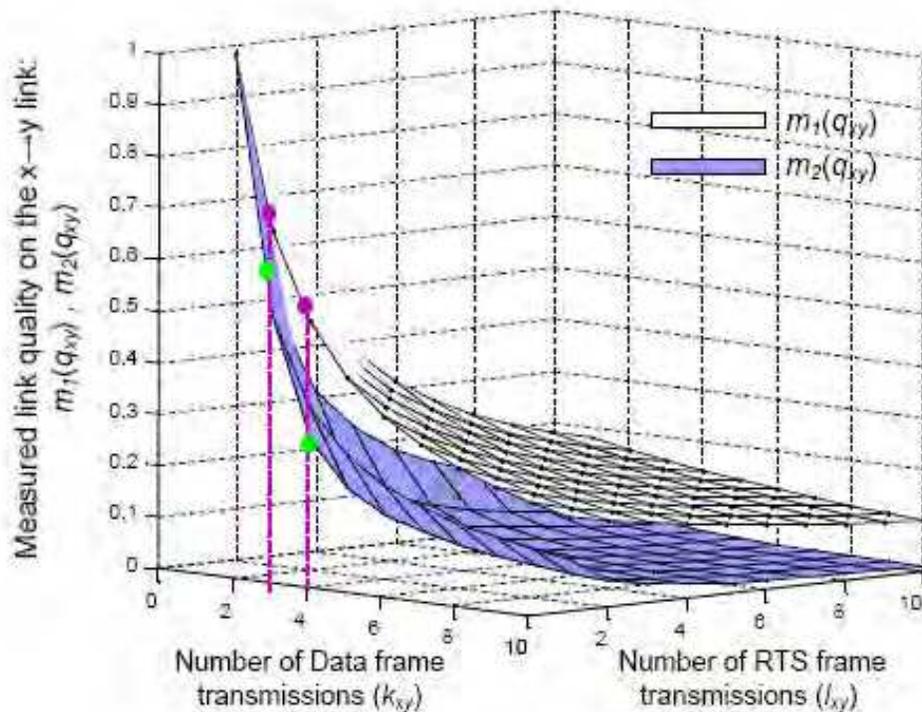


Fig. 3. Measured link quality using m_1 and m_2 function of the number of Data and RTS frames retransmissions.

From this point of view, the two metrics differ. Indeed, m_2 differentiates better than m_1 a small degradedness from a former high quality measured value. As clearly shown in Figure 3, both functions return 1 when no retransmission occurs which confirms the value of 100% success for the transmission while by lessening in link quality, m_2 drops more sharply than m_1 . For example, an increase in the number of data transmissions from 3 to 4 causes 32% decrease in m_2 and about 15 % in m_1 . Therefore, m_2 is called as Faster FTE (FFTE).

The variations of the metric with respect to quality changes can be evaluated using the sensitivity degree (Equation 3). Figure 4 compares the sensitivity degree of m_1 and m_2 using the difference $S_{m_1}(q_{xy}) - S_{m_2}(q_{xy})$. We see that for all the variations range of $k_{xy}(i)$ and $l_{xy}(i)$, S_{m_2} is larger or equal to S_{m_1} .

Consequently, m_2 has an even greater sensitivity in detecting changes in the estimated link quality than m_1 . m_2 obliges the routing agent to be more reactive and changes the selected route more often than m_1 .

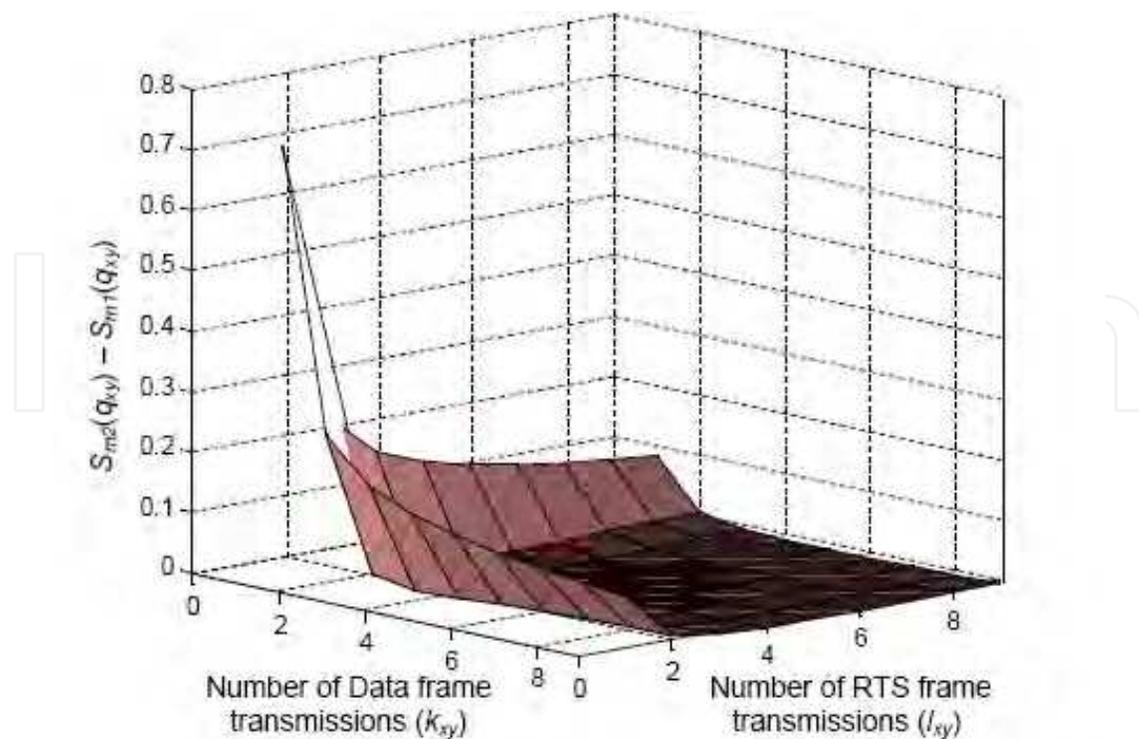


Fig. 4. Comparison of the sensitivity of the metrics m_1 and m_2 .

3.2 Simulation Study

This section presents simulation results to illustrate the performance of the link quality metrics compared to the Minimum Hop (MH) metric as the reference. Both m_1 and m_2 have been employed in DSDV (Perkins, 1994). The efficiency of the routes is estimated by multiplying the EWMA of m_1 values (or m_2) along the path towards the destination. This estimation of the link quality is piggy backed into the Hello messages that are sent in a periodic manner.

The simulations are performed under ns2.28 with the enriching the simulator in order to contain wireless channel fading effects, time variable link quality for wireless links, signal to interference and noise ratio, etc (cf. Karbaschi, 2008).

In order to show the impact of the link quality aware routing on the quality of service for a jitter-sensible flow, VoIP traffic is modelled and multiple random connections are set in a 30-nodes random topology. VoIP is basically UDP packets encapsulating RTP packets which contain the voice data. For accurately modelling the bursty VoIP traffic, Pareto On/Off traffic is used (Dang et. al, 2004), with different transmission rates corresponding to the widely used ITU voice coders.

Firstly, the impact of the sensitivity of the metric on the performance of the DSDV is evaluated and then the resultant instability and the generated jitter are investigated. T (resp. T_0) are used as the routing update period used in the case that m_1 and m_2 (resp. MH) are implemented

In order to unify the impact of the update period on the reactivity of the routing, T and T_0 are set to 15 s. The three metrics in terms of received throughput, defined as the average number of data bits received per second, are compared in Figure 5. The result of one connection confirms that both the link quality metrics are able to transfer more bits in

comparison to the MH metric in a time duration of 2000 s. Figure 5 also shows that m_2 outperforms the two other metrics. This confirms that m_2 , the more sensitive metric, is able to find a higher throughput path faster than m_1 and so reduces the packet drops.

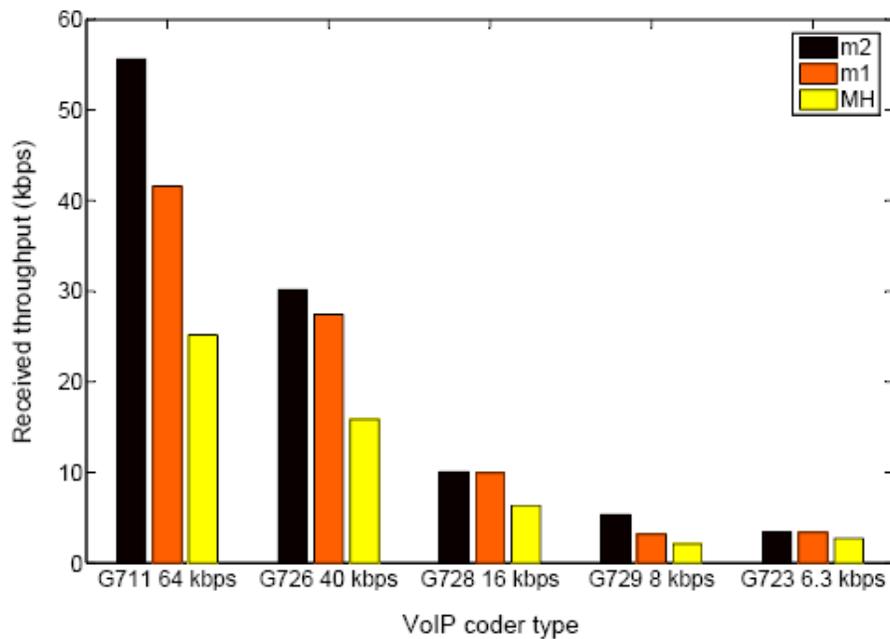


Fig. 5. Average received throughput with same routing update period ($T = T_0 = 15s$)

Comparing in Figure 6 the number of times that one dedicated flow flaps per second reveals that a link quality metric leads the routing to change the selected path more frequently. This effect is even greater when the sensitivity of the metric increases (m_2 compared to m_1). To show the impact of the metrics on the routing overhead, the average bit rate of control messages for the three metrics are compared in Figure 7. This reveals that the overhead generated by m_1 and m_2 are nearly the same and both more than MH's overhead. The reason is that the higher sensitivity of m_1 and m_2 generates more paths changes than MH. This obliges the nodes to piggy back more neighbors entries into their broadcast message and makes it larger, thus raising the routing overhead. Another cause of overhead increase is that a link quality metric needs a larger field in the control message than a hop metric (32 bits compared 16 bits). This enlarges the overall size of the control messages.

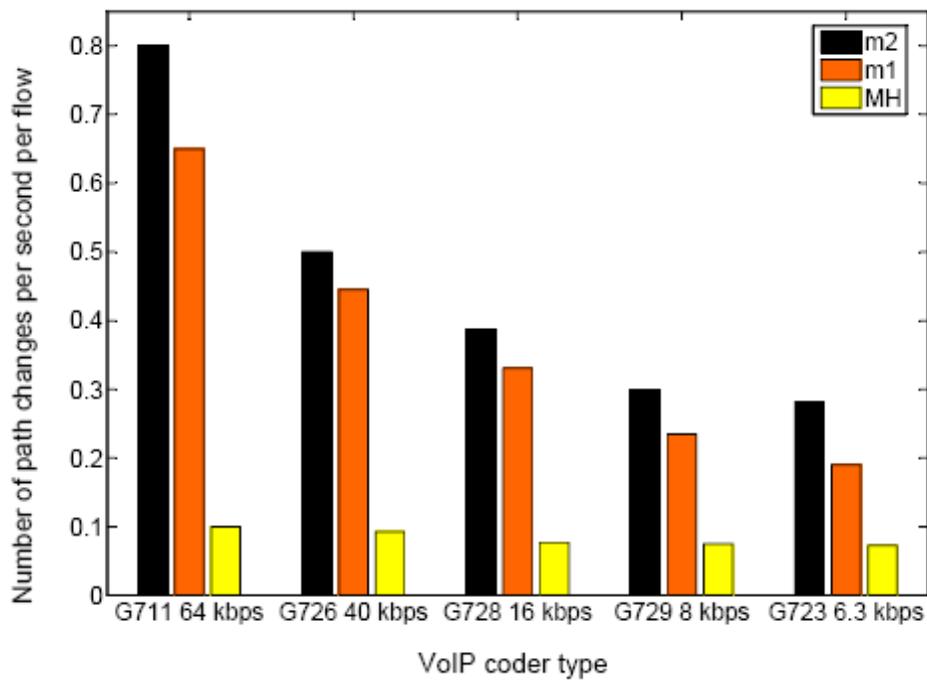


Fig. 6. Number of path changes per second per flow.

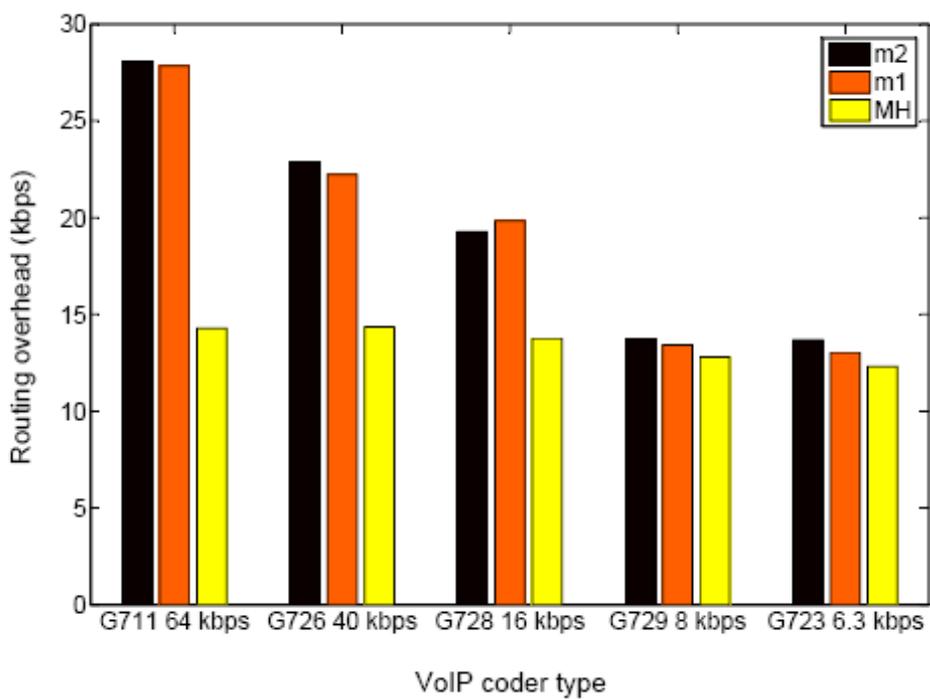


Fig. 7. Routing overhead for different VoIP coder types.

To see the efficiency of functionality of the link quality metrics, the evaluation is repeated by adjusting the amount of overhead to an identical value for the three metrics by tuning the value of T to 30 s. As explained in Section 3 this may reduce the throughput of m_1 and m_2 due to lower update rate of the metric. However, the average throughput comparison shows that m_2 still brings a much higher throughput (Figure 8).

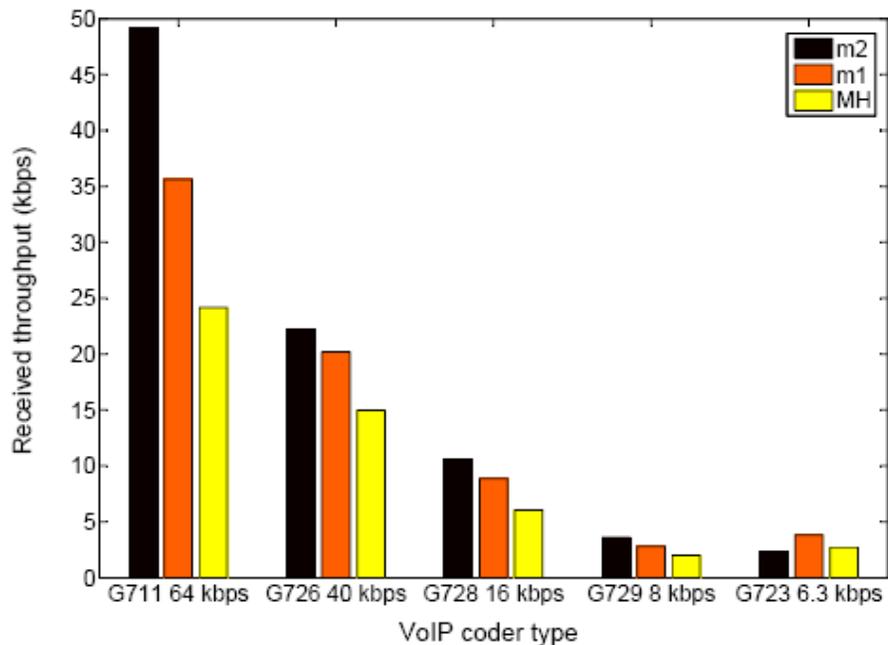


Fig. 8. Average received throughput with same overhead amount ($T = 30$ s, $T_0 = 15$ s) for different VoIP coder types.

Flapping the selected route may cause the consecutive packets to be routed through different routes. The subsequent instability of the selected path may cause a higher jitter level. Figure 9 illustrates the measured jitter per packet for the three metrics during a sample interval of a VoIP connection. Table 1 gives the mean and standard deviation of the jitter measured using the three metrics, which gives an idea of the spreading of the jitter distribution.

	MH	m_1	m_2
mean (ms)	9.5	9.6	9.43
std (ms)	20	25	30.2

Table 1. Jitter statistics

The jitter experienced using m_2 is much greater than the jitter observed with m_1 and MH. High jitter levels can have a great impact on the perceived quality in a voice conversation and as a result, many service providers now account for maximum jitter levels.

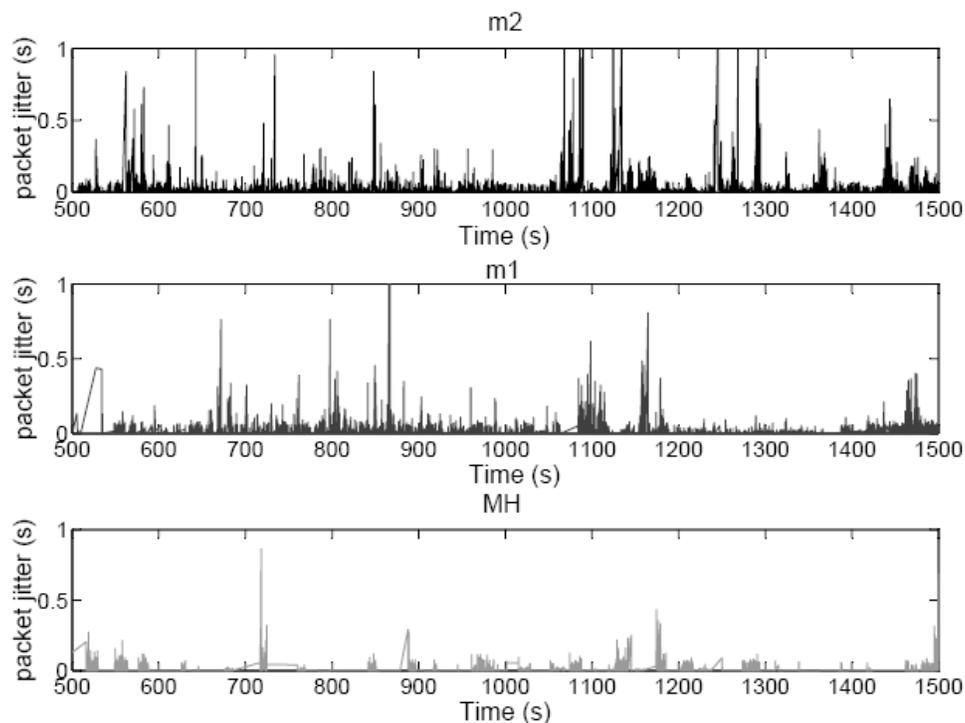


Fig. 9. Comparison of the jitter per received packet in a VoIP connection.

Most of the VoIP end-devices use a de-jitter buffer to compensate the jitter transforming the variable delay into a fixed delay (Khasnabish, 2003). Thus, high levels of jitter increase the network latency and cause a large number of packets to be discarded by the receiver. This may result in severe degradation in call quality. Therefore, real-time applications may not benefit from the higher throughput obtained with a more sensitive metric.

4. Conclusion

Wireless multi-hop networks are a promising technology to provide flexibility and rapid deployment for connecting the users at low cost. This chapter has examined the issues of link quality aware routing for wireless multi hop networks. Since the quality of wireless communications depends on many different parameters, it can vary dramatically over time and with even slight environmental changes. The peculiarity of wireless links and strong fluctuations in their quality lead to challenges in designing wireless multi hop routings. Therefore the necessity of having more efficient routing rather than the ones proposed for wired networks has arisen. Traditional hop count shortest-path routing protocols fail to provide reliable and high performance because of their blindness to under layer status. This draws lots research efforts to improve the routing performance through choosing good paths via transferring link status information from under layers.

This chapter addressed the stability issues of link quality aware routing which can be extremely important specially in providing quality of service for jitter sensitive applications. It was argued that having a reactive routing to cope with random changes of wireless links is essential. A quantitative tool for estimating the sensitivity of a link quality metric was introduced which indicated how strongly the metric reflects the quality changes. It was shown that the sensitivity has a great impact on the routing adaptivity. To illustrate this,

two comparable link quality metrics (FTE and FFTE) with different sensitivity were introduced and the routing performance observed with these metrics was compared by simulation. It was shown that having a sensitive metric can improve the routing functionality in terms of transferring a higher number of data packets through the network. However, one resulting side-effect is more oscillation in path selection. This leads to higher jitter level which a delicate application such as VoIP may not tolerate.

5. References

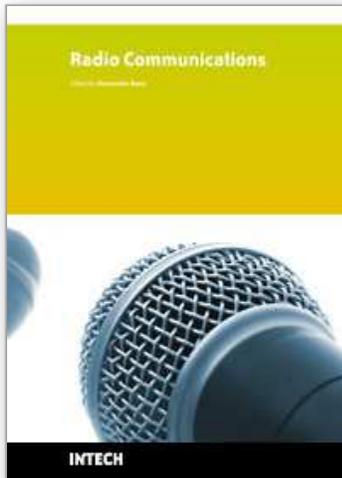
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In the last decades the restless evolution of information and communication technologies (ICT) brought to a deep transformation of our habits. The growth of the Internet and the advances in hardware and software implementations modified our way to communicate and to share information. In this book, an overview of the major issues faced today by researchers in the field of radio communications is given through 35 high quality chapters written by specialists working in universities and research centers all over the world. Various aspects will be deeply discussed: channel modeling, beamforming, multiple antennas, cooperative networks, opportunistic scheduling, advanced admission control, handover management, systems performance assessment, routing issues in mobility conditions, localization, web security. Advanced techniques for the radio resource management will be discussed both in single and multiple radio technologies; either in infrastructure, mesh or ad hoc networks.

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