# 1. Delay based solutions

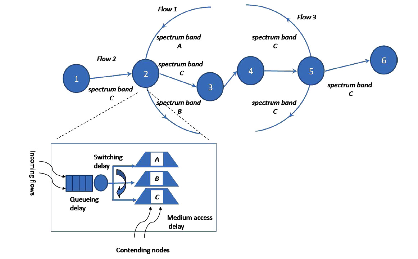
The quality of routing solutions can also be measured in terms of delays to establish and maintain multi-hop routes and to send traffic through the very same routes. Besides ‘‘classical” delay components for transmitting information in wireless networks, novel components related to spectrum mobility (channel switching, link switching) should be accounted for in multi-hop CRNs. Delay-aware routing metrics are proposed in [22–25], which consider different delay components including:

1. The Switching Delay that occurs when a node in a path switches from one frequency band to another;

2. The Medium Access Delay based on the MAC access schemes used in a given frequency band;

3. Queueing Delay based on the output transmission capacity of a node on a given frequency band.

Fig. 1 shows an example of these three delay components at a CR node. Node 2 relays flow 1 by receiving data on frequency band A and transmitting data on frequency band B. It uses the same spectrum band C for flow 2. On the other hand, node 5 relays all crossing flows on frequency band C. The delay at node 2 is dominated by switching delay, while the medium access delay is dominant in node 5. In addition to these delays, there exists also the queuing delay depending on the output capacity available on a given frequency band and on the number of flows sharing this capacity and on their workload.



Figure

## Solutions accounting for switching and access delay

The novelty of work in [22,23] is the introduction of a metric for multi-hop CRN which is aware of both the switching delay between frequency bands (Dswitching) and backoff delay (medium access delay) within a given frequency band (Dbackoff). At a relay node i, a metric representing the cumulative delay along a candidate route is computed as:



The first term takes into account the switching delay and backoff delay caused by the path and depends on the frequency bands assigned to all nodes along the path. As a consequence, DPi = Dswitching, i + Dbackoff, i. If the path is composed of H hops, the switching delay along the path is:



where k is a constant with the suggested value of 10 ms=10 MHz.

We notice that in some practical cases the switching time may be not a function of how wide the separation in frequency between two channels is (unless this requires a new transceiver to be activated). In this case the switching delay becomes a constant. The backoff delay depends instead on the bandwidth on the current frequency band, the number of consecutive nodes sharing the same frequency, and the packet size. The derivation of the expression Dbackoff, i is reported in [23]. The second term in the Eq. (2) accounts for the switching and backoff delays caused by existing flows at the relay node i. For the Dswitching formulation, the authors assume that the node scheduler serves the active bands in a round robin manner. The frequency band from a node’s active bands is denoted as Bandi. The number of active bands is assumed to be M. The Dswitching is formulated as:



and becomes a constant when there is no difference in switching from closer frequencies with respect to far away ones. Dbackoff is defined as the time from the moment a packet is ready to be transmitted to the moment the packet starts its successful transmission. It is obtained as:



where Numi is the number of contending nodes, pc is the collision probability, and W0 represents them minimum contention window size of a typical CSMA/CA wireless access.

## Solutions accounting for queuing delay

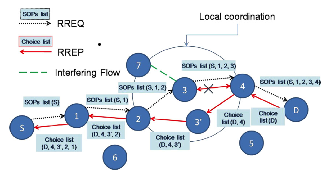
The metric in (2) is generalized in [24,25] where Dswitching and Dbackoff are integrated with a queuing delay arising at an intersecting relay node which serves n incoming flows. The expression of this queuing delay (named Dqueueing) is computed in [25]. The generalized cost function then becomes:



From the definition of this generalized metric, it is clear that assigning a new active frequency band to a flow results in a larger M and increases the Dswitching of Eq. (4). On the other hand, letting the flow use existing active frequency band Bandi increases Numi, making larger Dbackoff and Dqueueing. The effectiveness of this generalized metric is proven in the performance analysis of the paper in [25], where it is shown that the queueing delay estimation is fairly accurate, and the end-to-end delay provided by the proposed routing protocol outperforms traditional routing solutions.

Another contribution of the work [25] is the proposal of a local coordination of neighbor nodes started by an intersecting node. This node decides whether to accommodate an incoming new flow or to redirect it to its neighbors to relief locally the workload. This local coordination includes the operation of exchanging cost evaluation information with neighborhood and the redirection of the flow to a se- lected neighbor of the intersecting node. Both routing and spectrum assignment are based on the adoption of an on-demand protocol that is a variation of the Ad-hoc On-demand Distance Vector (AODV).

During the path set-up local state information are piggybacked into the route request packets and delivered to the destination node. It is important to note that this protocol does not rely on a simple list of intermediate nodes for routing: The Route Requests (RREQ), which are sent via broadcasting, contain locally obtained network state and deliver this detailed information to the destination, where they are processed to compute paths. The protocol operation starts with the source node broadcasting a RREQ message. As it is being forwarded, intermediate nodes add their own spectrum opportunities – SOPs, a list of currently available and unavailable channels – to the RREQ messages. Once a RREQ message reaches the destination, it estimates a set of cumulative delays based on possible local frequency bands it can use, following a queuing-based delay estimation method and using the metric of Eq. (6). Once it chooses the best possible frequency band it can use, it sends a Route Reply (RREP) message on the reverse path of the RREQ packet. All nodes along the reverse path process the RREP packet following the procedures of the destination. The similarities with the AODV protocols end at this point. The protocol envisions the possibility of changing the routing decisions as the RREP is forwarded along the reverse path. The rationale behind this lies in the fact that nodes carrying more than one flow may have to switch between two or more frequency bands, which in- curs a larger delay. Therefore, when a RREP packet is received by an intersection node, it checks its own neighbors to see if there is a better alternative to carry the flow in question. If any of the neighbors of the node that processes the RREP can provide a better delay, then the flow is routed over this new node and the previous hop is also notified of this change. Such an occurrence has been shown in Fig. 2. Here, the RREP packet traverses the same path as the RREQ packet up to node 3. At this point, node 3 estimates the delay to be large and locates another one of its neighbors, node 3’, which can carry the flow. Hence, node 3 notifies its upstream node 4 about this better alternative, upon which node 4 forwards the RREP packet over node 3’. The paths traversed by RREQ and RREP packets are shown in Fig. 2, as well.



Figure

## References

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