Broadcast Strategies with Probabilistic Delivery Guarantee in Multi-Channel Multi-Interface Wireless Mesh Networks

Carina Teixeira De Oliveira*, Fabrice Theoleyre¶, and Andrzej Duda*
*UJF-Grenoble 1, Grenoble Institute of Technology, CNRS Grenoble Informatics Laboratory UMR 5217, France
¶CNRS, University of Strasbourg, UMR 7005, France
Email: {oliveira,duda}@imag.fr, theoleyre@unistra.fr

***Abstract*—Multi-channel multi-interface Wireless Mesh Networks permit to spread the load across orthogonal channels to improve network capacity. Although broadcast is vital for many layer-3 protocols, proposals for taking advantage of multiple channels mostly focus on unicast transmissions. In this paper, we propose broadcast algorithms that fit any channel and interface assignment strategy. They guarantee that a broadcast packet is delivered with a minimum probability to all neighbors. Our simulations show that the proposed algorithms efficiently limit the overhead.**

***Index Terms*—Wireless Mesh Networks; multi-channel; multi-interface; broadcast;**

I. INTRODUCTION

We consider *wireless mesh networks* with routers based on the IEEE 802.11 technology. One way of improving their performance is to use multiple non-overlapping channels (free of inter-channel interference) so that mesh routers can transmit in parallel and without collision [1]. To take advantage of multiple channels, nodes need to have multiple IEEE 802.11 interfaces to simultaneously transmit/receive packets. A mesh router has to assign a set of channels to each of its interfaces and to allocate a set of its interfaces to each neighbor.

A few proposals focused on *broadcasts* in which a node wants to deliver a packet to all neighbors in the radio range even if some of them are tuned to different channels. Broadcast is important for various functions such as discovery or disseminating information, for instance in routing protocols. Most proposals for broadcast in multi-channel wireless mesh networks assume a static interface assignment in which all nodes are tuned to the same channels. Besides, no generic solution to cope with any channel and interface assignment strategy exists in the literature.

In this paper, we propose broadcast algorithms that fit any channel and interface assignment strategy guaranteeing a packet is delivered with a minimum probability to all neighbors. We provide simulation results to compare different strategies and choose the most suitable one for a given situation.

II. RELATED WORK

In multi-channel networks, each interface can be either static (it stays tuned to the same channel regardless of the time) or dynamic (it switches channels, but in a way that avoids deafness). Deafness may arise when the sender does not know the channel used by the receiver. Possibly, a multi-interface node can adopt a mixed approach maintaining one part of its interfaces static and another one dynamic.

A node can assign channels according to one of the following approaches:

1) Common Channel Set (CCS): the nodes may agree on using the same (common) channel set for all their static interfaces: the i^{th} interface uses channel i;
2) Pseudo-Random: each node pseudo-randomly assigns one channel per interface;
3) Adaptive: the protocol assigns channels in an adaptive way based on for instance measured interference or estimated load.

A multi-channel multi-interface strategy consists of a combination of *interface* and *channel* assignments [2]. We can identify the following strategies:

1) Static Interfaces/Common Channel Assignment: all interfaces are static and use the CCS approach (all nodes use channel i on the i^{th} interface).

2) Static Interfaces/Pseudo-Random Channel Assignment: all interfaces are static, but their channels are independent; this approach does not guarantee connectivity because of deafness: two nodes may choose different channels for their interfaces.

3) Dynamic Interfaces/Adaptive Channel Assignment: all interfaces are dynamic and use rendezvous to reserve timeslots with one neighbor to avoid deafness.

4) Mixed Interfaces/Common and Adaptive Channel Assignment: static interfaces use a common channel set (CCS) while dynamic interfaces act in an on-demand manner. For instance, static interfaces may be used to send RTS/CTS reserving the channel that will be further used by a pair of dynamic interfaces for the data exchange.

5) Mixed Interfaces/Pseudo-Random and Adaptive Channel Assignment: a node randomly chooses the channels used for its static interfaces; they are only used for reception. The transmitter has just to tune one of its dynamic interfaces to the channel used by the static interface of its neighbor.

A. Broadcast Strategies

Broadcast may be used for *discovery* (to find new neighbors), *local broadcast* (to send a packet copy to each neighbor) or for network wide *flooding*. We will focus here on local broadcast – we considered discovery broadcast elsewhere [3].

978-1-4577-0899-2/11/$26.00 ©2011 IEEE

Several papers tried to tackle the broadcast problem in multi-channel multi-interface wireless mesh networks. Qadir *et al.* [4] proposed to optimize the delay for multi-rate mesh networks. However, they focused on the global flooding problem, i.e. how each node in the network receives the flooded packets. [5] proposed to use additionally network coding to reduce the overhead. Xing *et al.* [6] proposed superimposed codes to tackle both the unicast and broadcast problems in multi-channel multi-interface mesh networks.

In conclusion, no proposal is sufficiently generic to deal with any Channel & Interface Assignment strategy.

III. BROADCAST ALGORITHMS WITH PROBABILISTIC DELIVERY GUARANTEE

In this section, we introduce the broadcast algorithms based on the classification proposed in Section II.

A. Probabilistic delivery guarantee

Transmission in wireless networks may suffer from errors due to various effects at PHY and MAC layers: attenuation, interference, fading, multipath propagation, synchronization errors, or collisions. Our goal is to design broadcast protocols that guarantee the reception of a broadcast packet by each neighbor with a certain probability.

1) Packet Error Estimation: We denote by p_e bit error probability and by p_p packet error probability. They are related by the following relation:

$$p_p = 1 - (1 - p_e)^{size} \tag{1}$$

where $size$ denotes the size in bits of a packet. p_{deliv} is the probability of successful packet delivery $p_{deliv} = 1 - p_p$. Since it depends on a given radio link, we use the notation $p_{deliv}(u, v)$ for the transmission from u to v.

2) Probabilistic guarantee: We propose a *probabilistic guarantee* of local broadcasts.

We consider that a particular neighbor is *covered* by a broadcast if it receives at least one copy of the corresponding packet with a probability superior or equal to $p_{cover_{min}}$, a parameter of the protocol. Higher layers may specify its value when they want to transmit a broadcast packet. A local broadcast is *successful* if all neighbors are *covered*.

Let $N(v)$ represents the neighbors of v. We denote by $p_{cover}(u \rightarrow v)$ the probability that node v correctly receives the broadcast of node u, i.e., v is *covered*. Our protocol will imply that

$$\forall v \in N(u), p_{cover}(u \rightarrow v) \geq p_{cover_{min}}. \tag{2}$$

To provide guarantees, we limit the links to those with packet error probability of at most $p_{p_{max}}$, i.e. a node does not maintain radio links of low quality.

B. Static Interfaces with Common Channel Assignment

With the common channel assignment, the i^{th} channel is assigned to the i^{th} static interface, so there is no deafness. Thus, broadcast is simple: a node has just to broadcast a packet through any of its static interfaces and all its neighbors will receive it.

A node has to send as many copies of the packet as required to cover each of its neighbors with the expected probability. If we consider packet losses uncorrelated among the different copies, the probability the node v receives at least one of the k copies from u is:

$$p_{cover}(u \rightarrow v) = 1 - (1 - p_{deliv}(u, v))^k \tag{3}$$

Finally, a node has to send the following number of copies so that v receives the packet with a probability superior to $p_{cover_{min}}$:

$$K = \left\lceil \frac{log(1 - p_{cover_{min}})}{log(1 - p_{deliv}(u, v))} \right\rceil \tag{4}$$

The link with the smallest p_{deliv} will determine the lower bound of the number of copies to transmit.

When only one static interface is tuned to the control channel, we can use this interface to send broadcast packets. However, the whole control traffic is concentrated on the control channel thus leading to its high utilization for large broadcast loads.

We can apply this approach to Strategies 1 and 4 (those that use a Common Channel Set) in Section II.

C. Static Interfaces with Pseudo-Random Channel Assignment

With this kind of assignment, a single transmission is not sufficient for local broadcast, because not all neighbors use the same channel. A node may have to send several packets so that all its neighbors become covered through different channels. In this strategy, each node knows the list of its neighbors and their static channels (this is a feature of the unicast protocol): a node will also use this information for its broadcast transmissions.

We propose a greedy approach inspired by MultiPoint-Relays [7]: a node chooses the minimum number of channels that cover the largest number of neighbors. More precisely, a node proceeds in the following way:

- a node constructs the list of its neighbors (i.e. all the nodes with which it has a common channel). It initially considers that all its neighbors are *uncovered.*
- while at least one neighbor is covered with a probability inferior to $p_{cover_{min}}$, the node searches for the channel with the best quality:
  - it counts the number of newly covered neighbors for each channel (their covering probability is inferior to $p_{cover_{min}}$);
  - it randomly chooses one of the best channels (to balance the load among channels);
  - for each neighbor reachable through this channel, it updates the probability of reception. It corresponds to the delivery probability for the link (u, v) if u did not yet schedule a packet for v. Otherwise, it recursively applies Equation 5.

$$p_{cover}(u, v) = 1 - (1 - p_{cover}(u, v)) (1 - p_{deliv}(u, v)) \tag{5}$$

We can apply this approach to Strategies 2 and 5 in Section II that use static interfaces to receive packets.

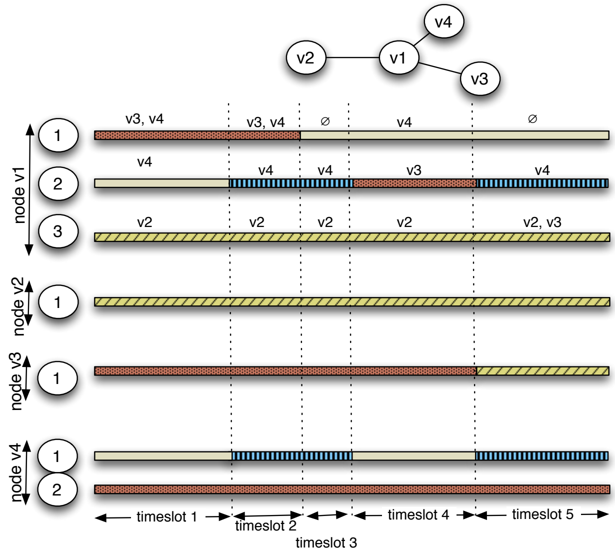

Fig. 1. Local broadcast with mixed interfaces—*each color of the bars represents a different channel and we report the list of neighbors reachable through each of v_1 interfaces at any instant (v_1 has 3 interfaces, v_2 and v_3 one interface, and v_4 2 interfaces). We consider in this example a neighbor covered if it received at least one copy*

D. *Dynamic Interfaces with Adaptive Channel Assignment*

When a node only uses dynamic interfaces, it needs to avoid deafness by correctly choosing both an interface and a schedule.

A node first creates the schedule of its interfaces and thus of its neighbors: a node knows the channel switching instants of all its neighbors for all their interfaces (otherwise transmissions are impossible due to deafness). It constructs timeslots so that itself and all its neighbors stay tuned to the same channel during one timeslot. We do not require all the nodes to switch their channels at the same time. Let us consider the example in Figure 1 in which timeslots are delimited by dashed lines: the first interface of node v_1 stays tuned to the same channel during timeslots 1 and 2 while the second interface switches between both timeslots. The schedule consists of a kind of the lowest common denominator between the different channel switching instants for all neighbors.

After having constructed this schedule, the transmitter is able to compute the number of neighbors that can be covered for each interface for each timeslot (i.e. when the channels match). Thus, it will re-iterate by greedily choosing pairs `<timeslot,interface>` that cover the largest number of not yet covered neighbors. When a node sends a copy of a broadcast packet, it updates the probability of delivery for each neighbor, adopting the same approach as precedent algorithm for common channel assignment. The algorithm stops when all the neighbors are covered with a probability superior to $p_{cover_{min}}$.

Let us consider the example in Figure 1. We consider in this example a neighbor covered if it received at least one copy. As explained previously, v_1 first computes *timeslots* (dashed lines). Then, it chooses the neighbors reachable through each interface for each timeslot and applies the greedy algorithm. For instance, node v_1 can reach node v_3 during the first timeslot through its first interface and node v_4 through the second interface of v_4. Finally, node v_1 may choose timeslot 1 via its first interface to cover v_3, v_4 and timeslot 1 via its third interface to reach node v_2.

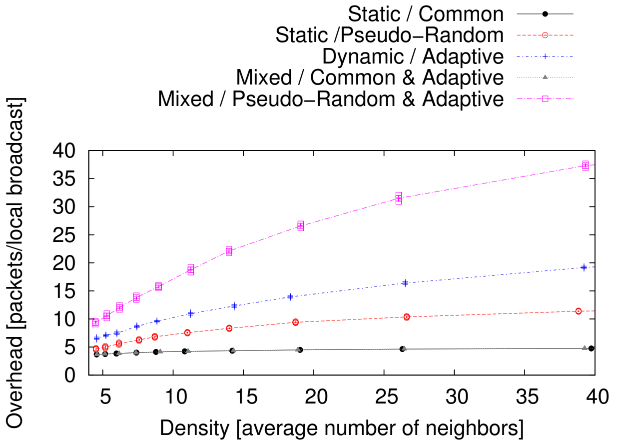

Fig. 2. Impact of the density on the overhead, 200 nodes, 3 interfaces, 12 channels

This algorithm can apply to the strategy that only uses dynamic interfaces (Strategy 3 in Section II).

IV. PERFORMANCE EVALUATION

We have implemented an opensource simulator to evaluate the broadcast performance [8]. We assume the ideal MAC layer to focus on broadcast performance with no collision. We generate random positions of nodes and plot 95% confidence intervals. By default, we consider networks of 200 nodes, with a density of 10 (avg. nb. of neighbors), 3 interfaces and 12 channels. A node is considered covered for $p_{cover_{min}} = 95\%$. Simulations measure the overhead defined as the average number of transmissions required by a node to cover all its neighbors. Because of lack of space, additional results may be found in our research report [9].

We denote each strategy as introduced in Section II and apply the broadcast algorithms defined in the previous section. In particular, we have implemented the Dynamic/Adaptive strategy in a way that each interface equally shares its time among all the channels following a pseudo-random sequence [10]. Two nodes are able to exchange packets if at least one pair of interfaces uses the same channel at the same instant.

Simulation takes into account packet error probability through the Packet Error Rate (PER) as modeled in [11]. The radio link is prefect under 100 meters, and a gray zone exists up to 400m: the PER depends non linearly on the distance (cf. [9] for more precise explanations). As explained above, the neighbors with a PER superior to $p_{p_{max}}$ have not to be covered. For the numerical results, we have chosen the value of $p_{p_{max}} = 0.5$ although different values would lead to consistently the same results.

a) Density: We have first evaluated the impact of the density on the overhead while maintaining the number of nodes constant (cf. Figure 2). Only Static/Common and

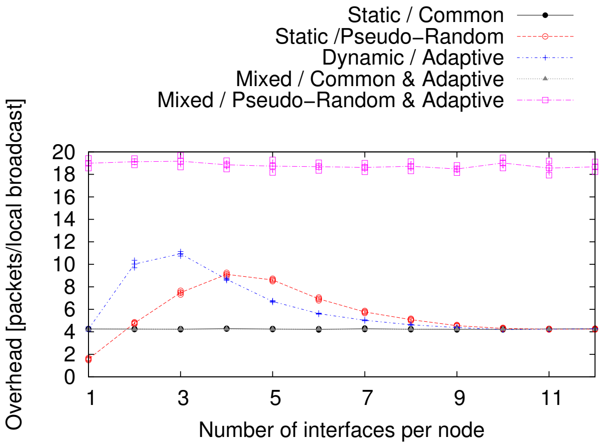

Fig. 3. Impact of the number of interfaces on the overhead, 200 nodes, 10 avg. neighbors, 12 channels

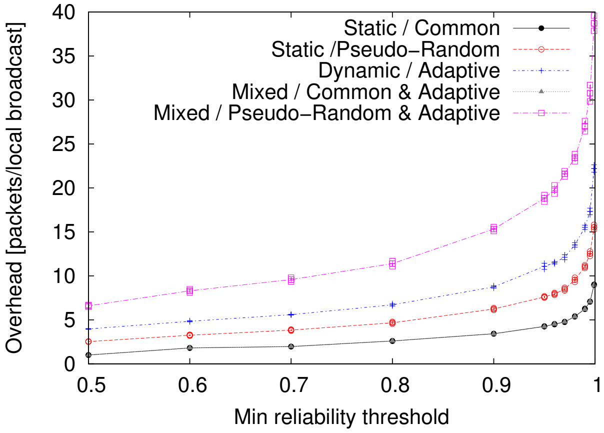

Fig. 4. Impact of threshold $p_{cover_{min}}$ on the overhead, 200 nodes, 10 avg. neighbors, 3 interfaces, 12 channels

Mixed/Common & Adaptive strategies have the same overhead, which is perfectly scalable, because they have a common channel set. The overhead created by our greedy algorithms tends to be stable when the density is large: they succeed to choose a minimum number of transmissions to guarantee the broadcast delivery.

b) Number of interfaces: We have also considered the influence of the number of interfaces (cf. Figure 3) on the overhead. The Dynamic/Adaptive and the Static/Pseudo-Random strategies tend to have initially a growing overhead: the number of neighbors to be covered increases since they have more chance to have a common timeslot. Then, the overhead decreases when it exceeds a threshold since the probability of having different neighbors that use the same channel increases with the number of interfaces. The Dynamic/Adaptive begins to be more attractive when the number of interfaces is large compared to the number of channels. The strategies using a common channel for broadcast are not impacted by the number of interfaces.

c) Impact of threshold $p_{cover_{min}}$: Finally, we have measured the impact of threshold $p_{cover_{min}}$ on the overhead in Figure 4. When $p_{cover_{min}}$ increases, the overhead becomes larger: neighbors with a large packet error probability may require the transmission of several copies. However, we can note that all the strategies follow the same trend.

V. CONCLUSION AND FUTURE WORK

We have proposed algorithms for local broadcast in multichannel multi-interface wireless mesh networks. In particular, they can cope with dynamic interfaces without a common control channel. To the best of our knowledge, these algorithms are the first ones to cope with deafness in this situation. Simulations show that all the strategies have an acceptable overhead and the load is fairly distributed among channels when the Common Channel Set strategy is not used. A greedy approach is particularly efficient to take advantage of the broadcast nature of transmissions.

We plan to study how we can deal with multiple rates: different bit rates may cover a different set of neighbors with different PER. We also plan to adapt the proposed strategies to dynamic conditions adopting an opportunistic approach. Besides, we aim at optimizing the delay, e.g. consider the question of which timeslot would present the best trade-off between the delay and the overhead when we use dynamic interfaces.

ACKNOWLEDGMENTS

This work was supported in part by the French Government (MESR) and the Competitive Clusters Minalogic and System@tic under contracts FUI SensCity as well as the French National Research Agency (ANR) project ARESA2 ANR-09-VERS-017.

REFERENCES

[1] P. Li, N. Scalabrino, Y. M. Fang, E. Gregori, and I. Chlamtac. How to effectively use multiple channels in wireless mesh networks. *IEEE Transactions on Parallel and Distributed Systems*, 20(11), 2008.
[2] W. Si, S. Selvakennedy, and A. Y. Zomaya. An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks. *Journal of Parallel and Distributed Computing*, 70(5), 2010.
[3] D. Abdelali, F. Theoleyre, A. Bachir, and A. Duda. Neighborhood discovery and activity monitoring in multichannel mesh networks. In *IEEE WCNC*, 2010.
[4] J. Qadir, C. T. Chou, A. Misra, and J. G. Lim. Localized minimum-latency broadcasting in multi-rate wireless mesh networks. In *IEEE WoWMoM*, 2007.
[5] Z. Yang, M. Li, and W. Lou. R-Code: Network coding based reliable broadcast in wireless mesh networks with unreliable links. In *IEEE GLOBECOM*, 2009.
[6] Kai Xing, Xiuzhen Cheng, Liran Ma, and Qilian Liang. Superimposed code based channel assignment in multi-radio multi-channel wireless mesh networks. In *MOBICOM*. ACM, 2007.
[7] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot. Optimized link state routing protocol for ad hoc networks. In *IEEE INMIC*, 2001.
[8] graphsim. http://forge.imag.fr/projects/graphsim.
[9] Carina Teixeira de Oliveira, Fabrice Theoleyre, and Andrzej Duda. Broadcast strategies with probabilistic delivery guarantee in multi-channel multi-interface wireless mesh networks. Research report, HAL http://hal.archives-ouvertes.fr/hal-00591986, May 2011.
[10] P. Bahl, R. Chandra, and J. Dunagan. SSCH: slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks. In *ACM MobiCom*, 2004.
[11] J. Camp, J. Robinson, C. Steger, and E. Knightly. Measurement driven deployment of a two-tier urban mesh access network. In *ACM MobiSys*, 2006.