Cross-Layer Routing in Wireless Mesh Networks

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Abstract— **Routing in Wireless Network is challenging because of the unpredictable behavior of the medium and the proactive effect of interference. In order to exploit all the advantages that the wireless medium offers, new routing metrics must be explored. These metrics should come from a cross-layer approach in order to make the routing layer aware of the local issues of the underling layers. In the present paper, we explore three primitive physical layer parameters: *Interference*, *Packet Success Rate*, and *Data Rate*. We define the metrics so that the routing level can correctly find paths that offer: low levels of generated interference, reliability in terms of Packet Success Rate, and highest available transmission rate. We prove that for cross-layer based routing, if the metrics are well designed, the problem is NP-Complete.**

I. Introduction

Wireless Mesh Networks appear as a promising technology to offer broadband wireless access to the Internet, but also to build self-organized networks in places where wired infrastructure is not available or not worthy to deploy. Mesh architecture is based on wireless mesh routers able to self-configure themselves as an access or a backbone network, offering connectivity to end-users by means of standard radio interfaces. Thus, Mesh Networks are a two-tier architecture. On the one side, mesh routers self organize themselves in order to form a wireless backbone, able to exploit all the benefits that the wireless medium may apport, through cross-layer routing. On the other side, each mesh router is responsible of forwarding traffic on behalf of all end-users that are in its coverage area. A logical separation is maintained between links connecting end-users to mesh routers, which are managed with a cellular approach, and links that form the mesh router's backbone, on which cross-layer routing is performed. If one or more wireless routers have a wired connection to the Internet, they act also as gateways, relieving the need to ensure one Internet connection per access points as in standard solutions.

Routing in these networking organizations is challenging, since the radio environment is hostile and unstable, and limited by interference, with new performance issues. De Couto *et al.* in [1] showed that, routing in multi-hop wireless networks using the traditional Shortest-Path metric is not a sufficient condition to construct good paths; *i.e.* able to effectively transport data with reasonable delay, throughput and reliability. Lundgren *et al.* in [2] have demonstrated that the multi-rate feature may lead to *gray-zones* of communications. Typically, radio interfaces offer several different transmission rates that the neighbor discovery algorithm coupled with the routing algorithm are not able to exploit. Indeed, different data rates have different transmission ranges; the lower the rate, the larger the range. Paths are usually set up by using broadcast messages sent at minimum rate, which may create routes formed by links that do not support higher rates.

Furthermore, routing algorithms do not take into account the interference they produce on a certain region of the network when they use a certain path to transmit packets, and a certain power at each hop. The consequence is that the global throughput capacity of the network is reduced, as shown by Gupta *et al.* in [3]. Each time a node transmits a packet, a perturbation is injected into the physical channel. Immediate neighbors must refrain from accessing the channel, while others observe a reduction in their performance due to higher interference and lower SIR (*i.e.* the Signal to Interference Ratio). In order to achieve globally higher network throughput capacity, the interference generated on each hop has to be limited as much as possible. A trade-off is necessary between opposite constraint: on the one hand, adding power increases the rate and reliability of transmission, and creates longer hops; on the other hand, more power means more interference, reducing the global throughput of the network.

The transmission power used for a packet is not usually an issue for the routing level, which is not aware of what is going on at lower layers. Classical architectures of wireless network follow a principle of separation between layers, neglecting important characteristics of their physical and link layers. The unpredictable behavior of the wireless channel has side effects on all the levels of the protocol stack. Dealing with these side effects is still an open research area. A cross-layer approach, breaking the separation between layers, might turn physical or link layer drawbacks into advantages, allowing full access to the benefits that wireless network may bring.

Since the shortest-path metric does not take into account the variable quality of the wireless link, other metrics, which are aware of the wireless nature of the underlying physical channel, must be explored. The objective is to provide the routing layer with an overall view of the MAC and PHY parameters and information, and allow it to control some of lower layers settings, in order to obtain improvements. Having a cross-layer approach for routing should help in finding paths that are reliable and efficient, as well as optimized in performance.

In this paper, we propose a cross-layer approach that uses Interference and Packet Success Rate (PSR), as perceived at

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the PHY-Layer, as long as raw physical data rate, as routing metrics. Moreover, the routing layer also optimizes the power used to transmit packets, depending on the intended next-hop, in order to maximize global throughput capacity. This can be formalized in a min-max problem: minimizing the interference to maximize capacity. We will prove that in this context routing is a NP-Complete Problem. Thus, also in the case of multi-metric cross-layer routing, heuristics developed for higher level QoS routing can be used.

The paper is organized as follows: section II explains the cross-layer approach; in section III and IV we detail the metrics; section V shows the framework of the routing algorithm and proofs the NP-Completeness of the problem; finally in section VI we give a snapshot of the work we are still doing on the topic and conclude the paper.

II. Cross-Layer Approach

In [3], Gupta and Kumar found that the average traffic carrying capacity λ that can be supported by a wireless multi-hop network is given by

$$\lambda(r) \leq \frac{16AR}{\pi\Delta^2 nLr} , \tag{1}$$

where A is the total area of the network, L is the average distance between source-destination pairs, each transmission can be up to a maximum of R bits/second, r is the transmission range, and n is the number of nodes in the network. The basic assumption is that there can be no other transmissions within a distance $(1 + \Delta)r$ from a transmitting node. The quantity $\Delta > 0$ models the notion of allowing only weak interference. Due to the inverse dependence of the right hand side on r, one wishes to decrease r by reducing transmission power. This, in turn, may decrease also R and, most of all, decrease the reliability of the available links. Equation (1) is the formalization of an intuitive behavior of wireless network: if we want to achieve high throughput, we have to maximize the data rate in transmission and to reduce the interference generated transmitting packets.

Rate and Interference depends of the power used to transmit. Thus, power control becomes a key factor to improve network throughput capacity. The way power is set is also a challenging task. The usual common power policy, where each node uses the same power level, is neither an optimal nor a flexible solution. In order to achieve a higher degree of flexibility, and also to improve throughput, a good policy can be to set the power depending on the next-hop the transmission aims to reach. The final target is to optimize the parameters of the lower layers on which routing is performed.

Several PHY-Layer parameters might be used to describe the quality and behavior of a wireless link. Interference and Data Rate are the natural choice in order to maximize global throughput capacity of the network, as consequence of (1). However, these two metrics do not give enough indication about the quality of the link. The link on which transmission is done with a limited amount of power may offer low interference and high nominal rate. Nevertheless, a larger number of losses may be experienced during data transmission on those links. Algorithms like Auto Rate Fallback ([4]) are not effective in this case, because they react only after a certain amount of losses. Furthermore, since this kind of algorithms is implemented in the MAC layer, they can react only to local conditions.

On the contrary, performing PSR estimation at the routing layer enables monitoring PSR along the entire path. Routing layer is able to react to bad channel conditions, by changing completely path in order to reach the same destination. In this way, only links with a certain level of reliability are chosen. The drawback is that in this way three metrics are used, which increases the complexity and the computational load of the routing layer.

Besides the implementation of the multi-metric routing protocol, some other parts of the protocol stack have to be enhanced. Mainly, the objective is to allow the cross-layer approach to take place, improving the interaction of the concerned layers. Information about the physical channel condition, *i.e.* the SIR, must be propagated from the PHY-Layer up to the Routing layer. A possible solution is to pass it as side information with packets. The transmission parameters, namely power and data rate, have to be propagated from the routing layer down to the physical interface. This can also be done by adding side information to packets.

The SIR used to perform estimation of PSR must be the SIR experienced on the intended receiver. We do not offer detail on this issue, observing that it is not difficult to obtain such measures. A solution may consist of adding a small overhead by piggy-backing the SIR value on the explicit ACKnowledge that every wireless MAC protocol uses.

Since each neighbor may sustain a different rate with a different power level, the neighbors discovery algorithm has to detect also the communication features toward each neighbor, in order to give to the routing layer the information it needs.

The detailed description of all the above mentioned mechanisms is outside the scope of this paper. We focus throughout the next sections on the routing algorithm, particularly on the proposed metrics.

III. Interference Estimation

The interference is the most limiting factor in wireless networks. It is also the most difficult parameter to control, since there is not a direct way to do it. Each node, in order to take the proper countermeasure on this issue, must be able to correctly estimate the interference it produces during transmission. The level of interference generated at each neighbor can be precisely calculated by adding the power perceived by each one. This approach is accurate, but also costly in resources and time since we need to scan the whole neighborhood, which has to send a feedback. Moreover, since a polling policy takes time, explicitly scanning the effects produced on each neighbor may lead to have stale information.

An alternative approach consists of defining a trend index function $I(\cdot)$ that preserves the key characteristics of real interference. Instead of performing direct measures, $I(\cdot)$ should be able to give a trend estimation, based on the knowledge of local parameters.

By *trend estimation* we mean that by minimizing $I(\cdot)$, the real interference is also minimized.

The function $I(\cdot)$ can be defined on the transmission power level P, and the number N of neighbors reachable with that particular level of power.

The key properties that $I(P, N)$ should preserve, if compared to real interference, are the following:

- If the number of neighbors N is constant changing the transmission power level from P_1 to P_2, the smaller the power level, the smaller the interference produced :

$$\forall P_1, P_2 \quad P_1 < P_2 \quad I\left(P_1, N\right) < I\left(P_2, N\right). \tag{2}$$

- If two nodes are using the same power level P but with different number of neighbors N_1 and N_2, then the level of interference decreases with the number of neighbors :

$$\forall N_1, N_2 \quad N_1 < N_2 \quad I\left(P, N_1\right) < I\left(P, N_2\right). \tag{3}$$

Note that the number of neighbors, *i.e.* the number of reachable nodes, is also a function of the power level used to transmit, $N(P)$. Indeed, using higher level of power enlarge the transmission range, in this way more nodes may be reached. Thus, interference can be expressed only in terms of power level P used to transmit, $I(P)$.

The following function $I(\cdot)$ validates the required properties:

$$I(P) = \frac{N(P)}{N(P_{max})}\sqrt{\frac{P^2 + P_{max}^2}{2P_{max}^2}},$$

where the number of neighbors $N(P_{max})$ are the nodes reachable with the maximal power level P_{max}, thus the largest neighborhood. The function can be extended to evaluate the interference generated over a network path:

$$\begin{aligned} I\left(Path\right) &= \sum_{\forall (i,j) \in Path} I_{i,j}(P_{i,j}) \\ &= \sum_{\forall (i,j) \in Path} \left(\frac{N_{i,j}(P_{i,j})}{N_{i,j}(P_{max})} \sqrt{\frac{P_{i,j}^2 + P_{max}^2}{2P_{max}^2}} \right), \end{aligned} \tag{4}$$

where $I_{i,j}$ is the interference produced to send a packet from node i to node j with power $P_{i,j}$, and $N_{i,j}(P_{i,j})$ is the number of neighbors of the sending node transmitting with power $P_{i,j}$.

It is noteworthy that the proposed definition, besides the transmission power, takes into account the number of neighbors that are really reachable around each transmitting node. The proposed estimation does not require any special feedback from neighbors, which are readily known by each node without adding any overhead or new neighborhood discovery protocol. The proposed trend index $I(\cdot)$ is very simple but describes properly the key issue of interference. A more detailed presentation of this interference index can be found in [5].

IV. Packet Success Rate Estimation

Most of the research in QoS has been devoted to the analysis of BER (Bit Error Rate), which gives insight to the mean behavior of the wireless network. Nonetheless, the mean behavior is not sufficient in a lot of scenarios, and a more precise characterization of the errors is needed. The analysis of error events is difficult because of the peculiar interaction between code specifics and physical channel effects.

For our purposes, the parameter of interest is the PSR, which gives an indication of the physical channel condition and quality at packet level. Supposing that the Packet Error Rate $PER\left(i, j\right)$ is independent over each transmission leg i to j, one can derive the PSR as

$$PSR\left(Path\right) = \prod_{\forall (i,j) \in Path} \left(1 - PER\left(i, j\right)\right). \tag{5}$$

In this work, the Packet Error Rate (PER) is not derived directly in the classical (and erroneous) manner. PER is typically derived with the hypothesis that errors are uniformly distributed in packet as $PER = 1 - (1 - BER)^L$, where L is the packet length. However, since errors at the output of a FEC decoder are not uniformly distributed, this leads to important overestimation of PER up to a factor of 10 for typical SIR. In [6], a new estimator of PER, which takes into account the burst structure of errors at output of Viterbi decoders, is presented. Viterbi decoders are nowadays largely used in wireless technologies, like UMTS and 802.11. It is shown that this result can be used to have precise and reliable estimates of PSR at the output of the physical layer.

V. Routing Problem in Wireless Network

Rate, Interference, and PSR are used as routing metrics in the effort to find paths that offer: large bandwidth (accordingly with hardware's limits); optimized global performances of the network; reduced interference injected by each packet transmission; reliability.

The problem is inherently complex, since three metrics are used. A possible approach might be to mix the metrics in a single one, like for example

$$C(path) = \frac{Interference(path) \cdot PSR(path)}{Rate(path)}, \tag{6}$$

where $C(path)$ indicates the cost of the path. The problem in this case is that the mixed metric may not exploit the real condition of the network. Indeed, on a path we can have very low PSR values and very high Interference, with a resulting global low cost. Clearly, in such a situation, the path is useless. Furthermore, the composition rule of a mixed metric may not be so easy to draw.

Using the three metrics separately allows modeling the state of the networks more accurately. Nevertheless, in wireless networks the three metrics are not completely independent. Power used to transmit has opposite impact on all of the three metrics. Since the routing layer has control on the transmitted power in our cross-layer approach, it may optimize the link behavior in order to create good paths. Performing

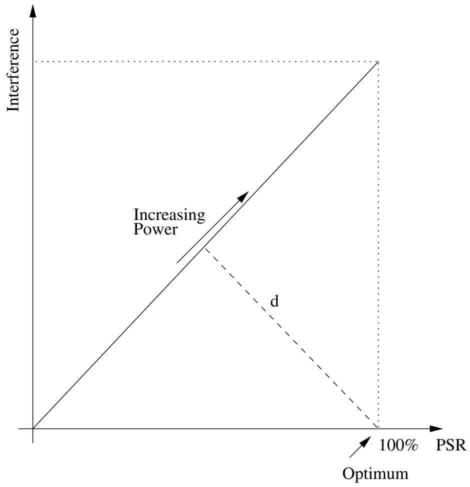

Fig. 1. Relation between Interference, PSR, and transmitting power.

this task, while, in parallel, searching also paths, increases enormously the complexity of the algorithm. The advantage would be the ability to find the global optimum state for the entire network. However, also if a heuristic exists to solve the problem, the convergence time would not be small. The risk is that the algorithm would not converge at all. Since each node changes its transmission power, this may induce a kind of *resonance* effect in the network. In this case, nodes would try to adapt themselves to the changing conditions without finding equilibrium.

In order to avoid such a situation, a solution is to perform the power optimization as a separated task from the paths searching task. Thus, the routing algorithm is split into two parts that must collaborate in order to perform optimal routing:

- Power Optimization Strategy
- Route Discovery and Update

In the next two subsections (V-A, V-B), we describe both tasks, while in section (V-C) we show how the two parts have to work together.

A. Power Optimization Strategy

The optimization strategy consists in finding the transmission power for each wireless link, offering the best tradeoff between PSR and Interference. To perform this task in a distributed manner, each node should locally optimize the power to use to communicate to its neighbors. Since this approach is based on a local optimization, we can not assure to reach the global optimum. However, performance can be improved.

Figure (1) shows the trend of the relation between Interference and PSR, with growing values of power. Clearly, the optimum is where 100% PSR is reached and there is no Interference produced. In practice, this point can never be reached, but, as shown in the picture, the distance d from it, can be minimized, just changing the power level. It is beyond the scope of this paper to present a detailed definition of d; however, the function may be as simple as the Euclidean distance.

Before describing the algorithm of power optimization let us introduce some notation. Let $\mathcal{N}$ be the whole neighborhood, *i.e.* the set of nodes that can be reached with the maximum power level and the lowest data rate. Let also $\mathcal{P}$ be the set of all available power levels, and $\mathcal{P}_j$ be the optimal power level to reach neighbor j. The distance from the optimum is a function of Interference and PSR, $d\left(I(p), PSR(p)\right)$, which, in turn, depends on the power level. Thus, the distance can be expressed as function of only the power level $d(p)$.

The steps that each nodes of the network must perform, in order to find the optimal power, are:

Step 1: $\forall j \in \mathcal{N}$, Set $\mathcal{P}_j = \mathcal{P}_{max}$
Step 2: Select $j \in \mathcal{N}$
Step 3: $\mathcal{N} = \mathcal{N} \setminus \{j\}$
Step 4: Find
$$\mathcal{P}_j = \{p \in \mathcal{P} | d\left(p\right) = \min_{\bar{p} \in \mathcal{P}} d\left(\bar{p}\right) \wedge R(p) = R_{max}\}$$
Step 5: If $(\mathcal{N} \neq \phi)$ then go to Step 2.

Note that the complexity of this approach is $O(|\mathcal{N}|)$, *i.e.* proportional to the number of neighbors.

B. Route Discovery and Update

Finding a path subject to multiple constraints is not an easy problem to solve. Knowing the complexity class in which it falls, can help in finding a set of algorithms able to solve it. Here we prove that the cross-layer approach we propose leads to an NP-Complete problem. This is the same class of problem as in multi-constraint QoS routing. Once we proved that the problem we formalized is NP-Complete, any of the heuristics developed for QoS routing can be used.

Since the Power Optimization Strategy applies only to links that offer maximum data rate, we can take into account only those links. This is like pruning the links that do not offer this behavior. Two advantages are brought by this choice. First, the complexity of the algorithm is reduced. Second, the issues arising with some kind of radio interfaces, namely 802.11b, where nodes transmitting with low data rates throttle the throughput of nodes transmitting at higher rates, is avoided.[1]

Theorem 1: The problem of finding a path, subject to the metrics *Interference* and *PSR*, is NP-Complete.

Proof: Wang *et al.*, in [9], proved that finding a path, subject to any two metrics with additive composition rule, as

$$f\left(ab + bc\right) = f\left(ab\right) + f\left(bc\right), \tag{7}$$

where ab and bc are two adjacent links, is equivalent to the PARTITION problem. The PARTITION problem can be formalized in the following manner: given a set of integers $\{a_1, ..., a_n\}$, determine whether there is a *partition* of the integers into two subsets such the sum of the elements in one subset is equal to the sum of the elements in the other. In [8], Garey *et al.* proved that PARTITION is a NP-Complete problem.

[1]This anomaly was extensively analyzed by Heusse *et al.* in [7].

The *Interference* estimation we defined in (III) follows this additive property

$$I\left(ab+bc\right)=I\left(ab\right)+I\left(bc\right), \tag{8}$$

where ab and bc are any two adjacent links. For *PSR*, the composition rule is

$$PSR\left(ab+bc\right)=PSR\left(ab\right)\cdot PSR\left(bc\right). \tag{9}$$

Nevertheless, the following transformation function can be introduced:

$$\overline{PSR}\left(x\right)=log\left(PSR\left(x\right)\right), \tag{10}$$

which changes the composition rule of PSR into

$$\overline{PSR}\left(ab+bc\right)=\overline{PSR}\left(ab\right)+\overline{PSR}\left(bc\right). \tag{11}$$

Equations (8) and (11) show that the metrics we proposed follow the composition rule (7), proving that the routing problem we have formalized is equivalent to the PARTITION problem, thus NP-Complete. ■

The above theorem can be interpreted in more general terms. Using a cross-layer approach, the routing based on sampling and control of primitive lower layer parameters is a NP-Complete Problem if the metrics are well defined. As final remark we can state that with the proposed metrics we have loop-free paths. Indeed, using additive metrics leads to avoid loops as proved in [10] by Garcia-Luna-Aceves.

C. Routing and Power Optimization

Interaction of the routing algorithm and the power optimization strategy is quite simple. Let us assume that the network is stable and that the neighbor discovery algorithm has been performed by each node. The next steps are to perform the power optimization strategy and the routing discovery algorithm. After this bootstrap phase, relaxing the assumption that the network is stable, what may arrive is that an event may change one of the metrics of one or more links. Usually, such kind of event triggers the routing algorithm to re-compute all paths concerned by the change. In the cross-layer approach, the only difference is that before triggering the routing algorithm, the power optimization strategy should be applied to the concerned links. The final result is that the computational load is increased. But, since the power optimization strategy is simple, the additional computational load is small.

VI. Conclusion and Future work

In this paper we proposed to use a new triple-metric (rate, interference, PSR) in order to deal with routing issues in wireless mesh networks. These metrics were defined based on a cross-layer approach that offers: (a) low levels of generated interference, (b) reliability in terms of Packet Success Rate, (c) higher available transmission rate. Compared to QoS Routing, the triple-metric we propose has two fundamental differences. Where QoS Routing might use several different metrics, like delay, bandwidth, jitter, to compute an optimal path, these parameters are observed at the network Layer. In our approach, instead, the routing is performed based on parameters measured at the PHY-Layer. Moreover, in our approach the network layer is able to set parameters of the physical layer, namely the transmission power, on a per-hop basis; in order achieve a global power optimization and throughput improvement, by local parameters control. This means to violate the traditional protocol layering, providing a cross-layer design of the routing mechanism. We proved that in such a scenario the routing problem is NP-Complete, as in the classical QoS Routing problem.

We are currently working on the design of the cross-layer approach. The goal is to give to the routing algorithm the means to control the interface settings, mainly transmission power, and get the right feedback from PHY-Layer.

Nevertheless, some issues are still open. The pruning strategy, for links that do not offer maximum rate, is not optimal and may introduce connectivity problems. The PSR may be highly variable because of the rapid evolution of channel conditions. The reaction to PSR changes should be tuned in order to not jeopardize the convergence of the routing algorithm.

References

[1] D.S.J. De Couto, D. Aguayo, B.A. Chambers, and R. Morris, "Performance of multi-hop wireless networks: Shortest path is not enough," *Proceedings of First Workshop on Hot Topics in Networks (HotNets-I)*, Oct. 2002.

[2] H. Lundgren, E. Nordström, and C. Tschudin, "Coping with communication gray zones in ieee 802.11b based ad hoc networks," *Proceedings of 5th ACM International Workshop on Wireless Mobile Multimedia (WoWMoM'02)*, Sept. 2002.

[3] P. Gupta and P.R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, Mar. 2000.

[4] A. Kamerman and L. Monteban, "Wavelan ii: A high-performance wireless lan for the unlicensed band," *Bell Labs Technical Journal*, 1997.

[5] L. Iannone and S. Fdida, "On the transmission effectiveness in multi-rate power-control capable wireless networks," *Proceedings of EUNICE 2003* , Sept. 2003.

[6] R. Khalili and K. Salamatian, "On the distribution of errors in convolutional codes," *Proceeding of IST'03*, Aug. 2003.

[7] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, "Performance anomaly of 802.11b," *Proceedings of IEEE INFOCOM'03*, Mar. 2003.

[8] M.R. Garey and D.S. Johnson, *Computer and Intractability - A Guide to the Theory of NP-Completeness*, Freeman, California, 1979.

[9] Z. Wang and J. Crowcroft, "Bandwidth-delay based routing algorithms," *Proceedings of IEEE GLOBECOM'95*, Nov. 1995.

[10] J.J. Garcia-Luna-Aceves, "A unified approach to loop-free routing using distance vectors of link states," *Proceedings of ACM SIGCOMM'89*, Sept. 1989.