Modélisation des réseaux IEEE 802.11 : Diviser pour régner

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Dans cet article, nous décrivons un modèle de réseau local sans fil qui estime le débit utile obtenu par chaque point d'accès. Les débits sont une fonction du graphe de conflit du réseau, des charges des points d'accès, de la taille des trames et des débits de transmission des liens. Notre approche de modélisation utilise une stratégie diviser pour régner qui divise le problème initial en plusieurs sous-problèmes, dont les solutions sont ensuite combinées pour fournir la solution au problème initial. En utilisant le simulateur ns-3, nous montrons que les erreurs relatives du modèle sont généralement inférieures à 10%.

Mots-clefs : WLAN, IEEE 802.11, Performance, Throughput, Conflict graph, Markovian, Divide-and-Conquer.

1 Introduction

Over the past two decades, Wireless Local Area Networks (WLANs) have been experiencing a growing presence in our daily lives, both in the number of connected devices and in the traffic volume they generate. Network administrators are continuously looking for solutions that improve the network's coverage and capacity, often leading them to deploy more and more Access Points (APs). As the WLAN grows denser and more complex with each new standard, simulating them becomes a more daunting task than ever. Hence, it is important to provide efficient and accurate analytical models to study the performance of the network. The pioneering work of Bianchi [Bia00] models the behavior of every single frame transmission. The author introduced a two dimensional Markov chain that models the backoff process taking place before every frame transmission in a fully-connected saturated network. Later works tried to alleviate the saturation constraint by adding a new state to the Markov chain that represents a node that has no frames to be sent [KS14] or by introducing the probability that a node has a frame waiting to be sent [FE11].

Other authors have decided to model the network at a high level of abstraction. Markov chains can also be used to model a network based on its topology where the states of the chain describe the set of nodes that are transmitting in the current network state. The model can then be used to estimate the throughput of the nodes [NK12] while taking into account the errors due to collisions and hidden terminals for a single-hop network, or to evaluate the fairness and spatial reuse in multi-hop, saturated networks with different carrier sensing and reception zones [DDT09]. In [WK05] CSMA/CA networks are modeled as continuous time Markov chains and the model is then used to study the fairness of the network. Jiang and Walrand [JW10] extend the usage of this model by proposing an adaptive solution that changes the nodes' backoff periods in the goal of maximizing the network's throughput and utilization.

In this paper, we study unsaturated, not fully-connected IEEE 802.11 wireless networks. We present a conflict graph-based modeling approach to discover the attainable throughput of each node. We apply a Divide-and-Conquer approach resulting in a series of Markov chains that together describe, at a high-level of abstraction, the current state of the entire wireless network. The conceptual simplicity of our model allowed us to fully automatize the procedure and to test it on networks of different sizes and topologies.

2 System Description

The system we consider is a Wireless Local Area Network (WLAN) implementing the IEEE 802.11 standard in its physical and medium access control layers.

Each WLAN is composed of network nodes which can be Access Points (APs) or the user stations associated to those APs. Every node has a *carrier sensing* (CS) range, i.e., a zone in which it detects the transmissions from other nodes. We refer to nodes that belong to each others' CS ranges as *neighbors*. The number of neighbors a node has greatly impacts its performance, as these neighbors have to share the available transmission capacity. Hence, we use CS ranges to build a *conflict graph* in which two vertices share a link if the corresponding nodes belong to each others' CS ranges. Given the dominance of download traffic (from AP to user station), we only represent the APs in our conflict graphs and our simulations show us that we can do so at the cost of a limited loss in accuracy. Figure 1 shows a network of six APs, where node 1 can simultaneously transmit with nodes 3, 5, and 6, but not with nodes 2 and 4.

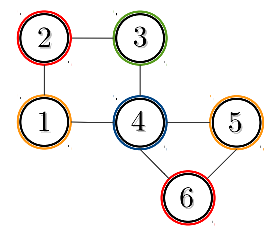

FIGURE 1: Conflict graph of a six-node network.

We denote by x_n (and y_n) the normalized *input rate* (and *output rate*) of node n. The input rate is simply the percentage of time a node wishes to occupy the medium, while the output rate is the percentage of time it achieves to occupy the medium. Note that we can easily derive the output rate of a node given its throughput (in Mbps) as :

$$y_n = \frac{t_n}{t_{n,max}} , \tag{1}$$

where t_n denotes the throughput achieved by node n, and $t_{n,max}$ is the maximum throughput node n can achieve if it were alone in the network.

3 Model

We provide below a brief review of our modeling framework. For a more detailed description we invite the reader to consult our previous work [SBB18].

3.1 Decomposition into subnetworks

The network decomposition is an approximation in which we consider a collection of (smaller) saturated networks, instead of the single network where nodes have varying input rates. In the original network, every node has a given input rate (Section 2) which is the result of the node having periods where it has frames to be sent (ON periods) and periods when its buffer is empty (OFF periods). In a subnetwork, every node is either ON or OFF, giving us a total of 2^N possible subnetworks for a network of N nodes. When a node is OFF in a given subnetwork, it is as if the node is completely removed, making the subnetwork smaller and easier to solve.

We consider the ON/OFF periods of all nodes to be independent of each other, allowing us to easily calculate the occurrence probability β_i ($i = 1, ..., 2^N$) of the subnetwork b_i as :

$$\beta_i = \prod_{n|b_i(n)=ON} x_n \prod_{m|b_i(m)=OFF} (1 - x_m) . \tag{2}$$

3.2 Solving each subnetwork as one or more Markov chain(s)

The first step to building the Markov chain(s) of each subnetwork is to define the states of the chain. Let us remind that knowing that a node is ON or OFF in a given subnetwork is not enough to tell if that node is in transmission or not. To remove the ambiguity we introduce the *sending states*, s_k (with $k = 1, \ldots,$). In every sending state, node n is either transmitting ($s_k(n) = \boldsymbol{1}$), or not ($s_k(n) = \boldsymbol{0}$). We use two simple rules to decide which sending states are possible for a given subnetwork : *i*) neighboring nodes cannot transmit at the same time, *ii*) if a node is ON and has no transmitting nodes then that node is transmitting. The first rule is inspired from the internal functioning of CSMA/CA where a collision occurs when neighbors transmit simultaneously, and the second rule captures the utilization maximization property studied in [DDT09].

Next, we decide which transitions are possible between sending states. Our reasoning is based on the fact that it is highly improbable for two nodes to start (or end) their transmissions at the exact same time. Thus, we consider that the transition from state s_k to s_ℓ is possible iff it satisfies that : *i*) no more than one node alters from $\boldsymbol{1}$ in s_k to $\boldsymbol{0}$ in s_ℓ, and *ii*) no more than one node alters from $\boldsymbol{0}$ in s_k to $\boldsymbol{1}$ in s_ℓ.

Once we have the states of the Markov chain and their transitions, we need to calculate the transition probabilities. We first introduce our definition of a *blocked node*. Any node that currently has a transmitting neighbor is said to be blocked, as it is unable to start a collision-free transmission. In the six-node network of Fig. 1, node 1 could be blocked by nodes 2 and 4. With this definition, we can calculate the transition probability from sending state s_k to s_{ell} as :

$$P_{k,\ell} = C \prod_{n|s_\ell(n)=\boldsymbol{1}} \frac{1}{1 + \sum\limits_{m \in w_n} \mathbb{1}_{b_i(m)=ON}}, \tag{3}$$

where w_n is the restricted neighborhood of node n, i.e., w_n contains all neighbors of n that are not blocked by some node different from node n, and C is a normalizing constant such that $\sum_{\ell \geq 1} P_{k,\ell} = 1$.

We then proceed to calculate the Markov chain's steady-state probability distribution. Note than certain transitions are considered to have a zero occurrence probability, potentially resulting in a subnetwork that has several irreducible Markov chains. Should that be the case, each irreducible chain is solved separately. However, we need to calculate the entry probability of each irreducible chain. The details of this computation are given in [SBB18]. The fundamental idea is that chains with more transmitting nodes have higher entry probabilities that those with less transmissions. The final modification to the entry probabilities is based on our simulation experience as well as the work of Chaudet et al. [CGLTG04]. Both studies showed that the nodes' transmission rates, frame sizes, and the IEEE 802.11 standard amendment in use have a high impact on the fairness of resource sharing. We implement this knowledge by slightly adjusting the chains' entry probabilities.

3.3 Combining subnetwork solutions

The final step in our modeling framework is to recombine all the probabilities we calculated for the subnetworks and calculate the output rate of the network nodes. The output rate of node n is :

$$y_n = \sum_{i=1}^{|B|} \left\{ \mathbb{1}_{b_i(n)=ON} \times \beta_i \times \sum_{m=1}^{M_i} \left(\widetilde{\omega}_i^m \times \sum_{k|s_k \in S_i^m} \left(\mathbb{1}_{s_k(n)=\boldsymbol{1}} \times \pi_i^m(k) \right) \right) \right\}, \tag{4}$$

where $|B|$ is the total number of subnetworks, M_i is the number of irreducible Markov chains for the ith subnetwork b_i. For the mth irreducible chain of subnetwork b_i we denote by $\widetilde{\omega}_i^m$ its entry probability, S_i^m the set of its sending states, and π_i^m its stationary probability distribution. Otherwise stated, y_n is simply the sum product of the probabilities of all the *subnetwork* $\times$ *Markov chain* $\times$ *sending state* combinations in which node n is sending. Using Eq. (1) we can then calculate the throughput of every node.

4 Numerical Results

To validate and assess the accuracy of our model, we performed extensive simulations using the discrete-event network simulator ns-3. Our simulations include modifications in the network topology, frame size, transmission rate, frame aggregation, as well as different IEEE 802.11 standard amendments. In the interest of brevity, we only show a single example here while more results are available in [SBB18].

We consider the six-node network of Fig. 1 and the case where the input rates of the first five nodes are fixed ($x_1 = 0.5$, $x_2 = 0.4$, $x_3 = 0.6$, $x_4 = 0.3$, $x_5 = 0.7$) while the last node has an input rate varying in [0,1]. Figure 2 shows the results obtained in simulation and the estimation of our model where the nodes are labeled N1 to N6. We notice that the model accurately captures the tendencies of all the network nodes. The nodes most affected by node 6's changing input rate are of course its neighbors, however the model also reproduces the behavior of the other nodes whose output rates are only slightly affected.

Using the same network, we executed five other simulation scenarios in which the input rate of one of the other five nodes varies. We obtained an overall relative error of 9.8% with a median of 9.77%. We found that these values are representative of all the different simulation scenarios we tested.

As WLANs tend to be more and more centralized, we believe there is an increasing number of possible applications for our model. The proposed model can be used to find the optimal configuration of a WLAN depending on the topology and/or the traffic demands. Because the model is fully automated, we were able to use it to find the optimal channel assignment for a network with a random topology, or to study the performance benefits of upgrading the IEEE 802.11 standard amendment. We invite the reader to consult out previous work [SBB18] for a detailed explanation of several possible applications.

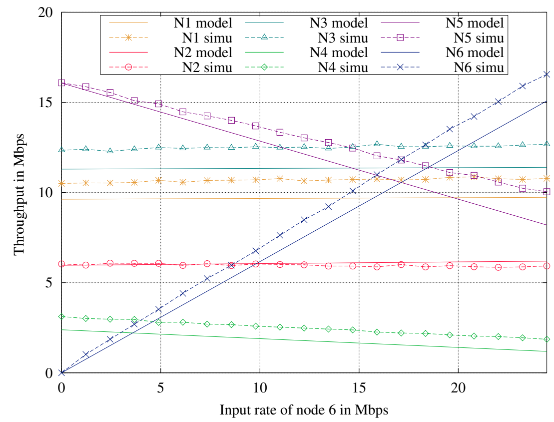

FIGURE 2: Six-node network : varying the input rate of node 6, x_6.

5 Conclusion

We presented a modeling framework for IEEE 802.11-based WLANs. Our approach accounts for WLANs composed of multiple APs assuming their conflict graph is known. Our framework is used on WLANs that have APs with arbitrary load levels, frames sizes, and transmission rates. The proposed solution revolves around a Divide-and-Conquer approach to split the initial problem into many sub-problems, each being of much lower complexity.

Our simulation results show that our model was able to forecast with a reasonable degree of precision (typically within 10% of relative errors) the mean throughput attained by each AP of the network.

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