Evaluation of Various Interference Models for Joint Routing and Scheduling in Wireless Mesh Networks

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***Abstract*—We explore radio resource allocation in Wireless Mesh Networks, namely we study how to determine a space- and time-division pattern of transmissions, to deliver traffic to gateway nodes. We highlight link scheduling and routing issues, which we investigate in a cross-layer framework. To this end, an integer linear program is presented, where diverse constraints affect resource allocation; in particular, we focus in this paper on the key role played by the characterization of radio interference. Finally, we obtain numerical results through a genetic algorithm, and we are able to show that the wireless interference model adopted strongly affects the performance of the radio resource allocation; thus, an accurate representation of the wireless channel is necessary to obtain meaningful results.**

***Index Terms*—Interference models, Routing, Scheduling, Wireless Mesh Networks, Genetic Algorithms.**

I. Introduction

Wireless Mesh Networks (WMNs) [1] represent a promising technological solution to provide end users with broadband wireless connectivity. In WMNs, a first tier comprises the mobile end terminals, called Mesh Clients (MC), which are connected through a one-hop wireless link to a fixed infrastructure node, called Mesh Router (MR). Multiple MRs are interconnected in a multi-hop fashion, thus realizing a second tier, called the *network backbone*. The connectivity of this second tier is improved by deploying additional MRs, which are typically low-cost terminals. As the network backbone is entirely wireless and stationary, it eliminates the need for cables and further problems related to mobility, such as battery saving, as the MRs can be plugged to a power outlet.

In general, to attach the WMN to the Internet, some special MRs, called Mesh Access Points (MAPs), are equipped with wired connections and therefore can take the role of Internet gateways. They usually are more computationally powerful than plain MRs, which simply work as relay nodes.Due to the higher cost of such nodes, their number is reasonably limited, e.g., just one or two MAPs are used. The connection in the first tier (from any MC to its related MR) can be assumed to employ a widespread cost-effective radio technology, e.g., IEEE 802.11 [2]. Instead, the backbone poses interesting challenges, especially for link scheduling and routing [3], [4].

As pointed out by [5], combining optimal link scheduling with sub-optimal routing or vice versa results in an overall poor performance; in other words, scheduling and routing impact on each other and their optimality is strongly coupled. This is mainly due to the limitations imposed by the radio interference; the wireless medium allows simultaneous communications only if they do not interfere. Therefore, [5] concludes that interference-awareness available at the link layer must be exploited at the routing level. For this reason, several researchers [3], [6]–[8] have proposed a cross-layer approach, which we also adopt in this paper, so as to realize a Joint Routing and Scheduling (JRS) framework.

In particular, in this work we will discuss space- and time-division multiple access (STDMA) models of JRS [7], focusing on the case of traffic delivery from all MRs to the MAPs. To this end, we present an Integer Linear Programming (ILP) framework, where we put special emphasis on wireless interference, in order to compare existing approaches such as the so-called protocol [6], [8] and physical [3], [4] models. We stress that the main contribution of the present paper is not in the optimization framework for JRS, where we utilize existing models of flow delivery problems. Instead, a main original element of our model, which up to our knowledge has never been analyzed in deep detail, is to investigate the impact of the interference model chosen.

We remark that this aspect can not be regarded only as a free choice in which all the possibilities are equivalent. Considerations about realism and applicability of the solution demand a careful choice in this sense. Another novel point of our contribution is that, to solve the JRS problem, we use a Genetic Algorithm (GA), a technique which has proven itself as well capable to deal with the complexity of the optimization resulting from traffic and interference constraints. GAs are particularly appropriate for ILP originated from wireless networking, and we showed in [9] that for JRS problems they offer a good trade-off between accuracy and computational complexity.

The main findings of our investigation are that various interference models, though qualitatively similar in describing the general trend (i.e., the delivery time increases with the amount of traffic), are significantly different from the quantitative viewpoint. Especially, the so-called protocol interference model may heavily limit the network parallelism. This mandates for a careful choice, aimed at guaranteeing consistency with reality of the results, and at the same time properly exploiting the wireless medium in order to provide end users of the WMN with adequate network capacity. In other words, the results shown in this paper are not only introduced to verify the optimization framework, but also to quantify the differences of the models available, which, if neglected, may cause an erroneous and unrealistic performance evaluation.

The rest of this paper is organized as follows. In Section II we outline the notation and the JRS problem. We state the optimization constraints in Section III and IV. In Section V we outline a GA to solve the problem and in Section VI we show numerical evaluations for various interference characterizations. Finally, we conclude in Section VII.

II. Notation and Problem Statement for JRS

We represent the WMN backbone by means of a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{E})$. The *nodes* in set $\mathcal{N}$ are the MRs, which are in turn linked through *directed edges* belonging to set $\mathcal{E} \subseteq \mathcal{N}^2$, i.e., ordered pairs of nodes representing the communication links of the backbone. The link where node $i \in \mathcal{N}$ transmits to $j \in \mathcal{N} \setminus \{i\}$ is represented by edge (i, j), which is included in $\mathcal{E}$ only if j can receive a transmission from i in the absence of any *source of disturbance* due to wireless interference.

To formalize this concept, we associate each ordered pair of nodes $(i, j) \in \mathcal{N}^2$ with a parameter g_{ij}. This value represents the wireless link gain, i.e., the ratio between received and transmitted power, of a transmission from i to j. For the sake of simplicity, we include in this term also background noise effects and we normalize all transmit power values to 1. This can be done by properly re-scaling the g_{ij} terms if power levels are fixed. Otherwise, it is possible to extend the analysis to power-controlled networks by following [3]. Finally, we assume that g_{ij} is fixed and known in advance. Actually, in practical cases g_{ij} is variable over time, but we can reasonably assume the availability of a conservative estimate, i.e., with a margin, including fast fading and other non-ideality phenomena [10]. Since the nodes are stationary, any variation of g_{ij} is in fact expected to be relatively limited. Thus, we can define the practical rule that an edge $e = (i, j)$ belongs to $\mathcal{E}$ if and only if g_{ij} is above a given threshold.

Moreover, we need to formalize who are the sources of disturbance indicated above. These are necessarily other nodes in the network, all of which, from a general perspective, are potential sources of disturbance. However, it is meaningful to restrict this concept, intuitively speaking, by eliminating very far nodes. Surely, if i is able to transmit to j, i.e., $(i, j) \in \mathcal{E}$, it is also able to cause disturbance. Yet, successful communication is a more restrictive requirement than disturbance, since it is possible to jam the reception of another node without being able to transmit to it. To this end, we extend $\mathcal{E}$ to another set $\mathcal{E}' \subseteq \mathcal{N}^2$ by adding *virtual* edges, not representing physical communication links but only disturbances due to interference. According to what discussed above, $\mathcal{E} \subseteq \mathcal{E}'$. A definition of $\mathcal{E}'$ based on the values g_{ij} could be introduced similarly to the one of $\mathcal{E}$, i.e., by selecting a threshold on the gains, lower than the one of $\mathcal{E}$. In some approaches [4], this formulation based on path gains is replaced by simpler considerations about node distances, which in turn implies that the path gains are assumed to be solely based on distance.

Finally, we denote with $\mathcal{R}_i$ and $\mathcal{S}_i$ the set of the *one-hop output and input neighbors* of i, respectively, i.e., $\mathcal{R}_i = \{j \in \mathcal{N} : (i, j) \in \mathcal{E}\}$, $\mathcal{S}_i = \{j \in \mathcal{N} : (j, i) \in \mathcal{E}\}$. Similarly, we construct $\mathcal{R}'_i$ and $\mathcal{S}'_i$ by looking at the extended edge set $\mathcal{E}'$.

We instantiate the JRS problem in a STDMA context, i.e., we consider a discrete (slotted) time t, and synchronous transmissions lasting for an integer number of time-slots. We speak of *activation* of edge (i, j) at time t, if i transmits to j at time t, and we define a binary variable $x_{ij}(t)$, equal to 1 if (i, j) is active at time t, and to 0 otherwise. The JRS problem corresponds to assigning a suitable binary pattern of these variables over t, which determines medium access (and therefore scheduling) and also creation of routes (by tracking time-multiplexed activations on subsequent links).

In this paper, we focus on the problem of delivering a given amount of traffic from non-gateway MRs to the MAPs within T time-slots. This means that the valid time instants to activate links are $t \in \mathcal{T} = \{0, 1, 2, \ldots, T - 1\}$. Several values of T can be tried, in order to possibly identify a minimum. With minor modifications, this approach can be used to solve similar problems, e.g., where instead of minimizing T, we maximize the load delivered over time (i.e., throughput maximization) or we take into account additional fairness or priority issues.

For simplicity, we assume that the initial backlog of each MR is known a priori and no further arrivals occur after time 0. This formulation can be similarly extended to more general cases where additional backlog traffic at each MR is dynamically generated over time. Also, it is not restrictive to focus on the case where a single MAP is present, denoted with $y \in \mathcal{N}$. The generalization to multiple gateways is entirely straightforward. The backlog of the nodes, expressed in *packets*, i.e., units of traffic, evolves over time. At time t, we denote the backlog of node $i \in \mathcal{N}$ with $q_i(t)$. This variable can take values for t going from 0 (initial backlog assignment) to T (final backlog, which ought to be 0 for all the nodes but y). Finally, we relate each $(i, j) \in \mathcal{E}$ with a value r_{ij}, also constant and known a priori, determining the packet amount which can be sent on a time-slot from i to j.

When determining the link activation pattern, we see that network, medium access control (MAC) and physical layers impose certain limitations which, using the language of optimization theory, will be referred in the following to as *constraints*. In the sequel, we will investigate their impact on network performance; in particular, this discussion develops in two parts. First, we will talk about the constraints involving either the traffic delivery, called *flow constraints*, or the physical capabilities of the radio terminal, called *transceiver constraints*. Second, we will describe the constraints specifically related to interference, also referring to models available in the literature. In order to avoid cumbersome notations in the constraint formulations, we will hereafter write $\forall(\mathbf{NT})$ for $\forall i \in \mathcal{N}$, $\forall t \in \mathcal{T}$ and similarly $\forall(\mathbf{ET})$ for $\forall e \in \mathcal{E}$, $\forall t \in \mathcal{T}$.

III. Flow and Transceiver constraints

The constraint discussed in this section relate to fundamental aspects of the problem under exam which are unaffected by the choice of the interference model. In particular, we need to discuss two kinds of constraints. The former, which has a broader extent than just wireless networks, relates to the general formulation of flow delivery problems, where flow conservation must be imposed at each node. The latter depends on that, in wireless networks, node capabilities for transmission and reception are limited. Indeed, we assume that the mesh nodes operate with a single omnidirectional antenna on narrow-band channels; thus, they can not receive simultaneously from multiple sources in the same time-slot. Similarly, even though the wireless medium is broadcast, we focus on unicast transmissions, so the transmitter can send out only one signal at a time with one intended destination.

Flow conservation at each node corresponds to imposing that, for all $i \in \mathcal{N}$, the residual backlog at any instant t equals the backlog at time $t-1$, plus the received and minus the transmitted data on time-slot $t-1$. Formally,

$$\forall(\mathbf{NT}): \quad q_i(t) = \max(0, q_i(t-1) - \sum_{j\in\mathcal{R}_i} x_{ij}(t-1)r_{ij}) + \sum_{j\in\mathcal{S}_j} \min(q_j(t-1), x_{ji}(t-1)r_{ji}) \qquad (1)$$

Moreover, we need to impose that, after the T slots of interest, all the traffic is delivered from each node to the gateway y, which conversely has no backlog at time 0.

$$\forall i \in \mathcal{N}\setminus\{y\}: \qquad q_i(T) = q_y(0) = 0 \qquad (2)$$

Note that these constraints follow a very general formulation and do not depend on the wireless properties of the network. Therefore, we further introduce the transceiver constraint, imposing that the maximum number of simultaneous transceiver operations (i.e., either transmission or reception) is one. Thus:

$$\forall(\mathbf{NT}): \quad \sum_{j\in\mathcal{S}_i} x_{ji}(t) + \sum_{j\in\mathcal{R}_i} x_{ij}(t) \leq 1. \qquad (3)$$

IV. Wireless Interference Constraint

Additionally to the constraints discussed previously, we have the *wireless interference constraint*. The most widely used classification of interference models in the literature dates back to [11] and distinguishes between the so-called *physical* and *protocol* interference models. In the former, the feasibility of simultaneous link activations is determined by the Signal-to-Interference-plus-Noise-Ratio (SINR) of all receivers being above a given threshold. The latter imposes instead simpler interference conditions modeled through graph neighborhood relationships.

Hereafter, we will refer to the taxonomy reported in [12] to sort out different versions of these models. In particular, according to this classification, the protocol model can be regarded as a class of conditions, which generically describe interference as a binary *conflict* relationship defined between edges [4], [5], so that two conflicting edges can not be simultaneously activated. For any edge $e = (i,j) \in \mathcal{E}$, one can define a *conflicting set* $\mathcal{I}(e) \subseteq \mathcal{E}_{ij}$, where $\mathcal{E}_{ij} = \mathcal{E} \cap (\mathcal{N}\setminus\{i,j\})^2$, containing all edges conflicting with e. We remark that, differently from other formulations [6], [8], we explicitly exclude edges involving i or j from the conflicting set as the simultaneous activation of such a link with (i,j) is *already forbidden* by the transceiver constraint (3).

The required condition is that if edge e is active, no edge in $\mathcal{I}(e)$ can be active. Formally,

$$\forall(\mathbf{ET}): \quad \sum_{f\in\mathcal{I}(e)} (x_f + x_e - 1) \leq 0\,. \qquad (4)$$

Note that in certain papers this condition is stated as simply imposing the sum of x_f over $f \in \mathcal{I}(e)$ to be zero. This is, however, *incorrect*, as this must hold only if that e is active, because any two edges of $\mathcal{I}(e)$ conflicts with e but not necessarily with each other. In the correct formulation, reported in (4), this is taken into account, since if $x_e = 1$ all x_f must be zero, whereas if $x_e = 0$ the constraint is trivially verified, as each summation term, which becomes $x_f - 1$, is not greater than 0.

In the literature, many definitions of $\mathcal{I}(e)$ can be found, according to the context and the underlying MAC. In [12], we reviewed and classified them as follows.

01protocol model – In this case, we set $\mathcal{I}(e) = \mathcal{E}_{ij}$ for all $e = (i,j) \in \mathcal{E}$, i.e., at most one edge can be active at any given time throughout the whole network. This is the most conservative protection against interference. Actually, this is not proposed as a realistic model, but only as a useful term of comparison, since it sets a performance bound: no interference model can achieve worse performance in terms of parallelism.

11protocol model – This model assumes that $e = (i,j)$ is conflicted with by those links whose transmitter or receiver (or both) are able to disturb i or j (or both). Thus, the conflicting set of edge e is

$$\mathcal{I}(e) = \{(k,\ell) \in \mathcal{E}_{ij} : \{i,j\} \cap (\mathcal{R}'_k \cup \mathcal{R}'_\ell) \neq \emptyset\}. \qquad (5)$$

16protocol model – This model assumes that only external *transmitters* disturb $e = (i,j)$, which happens if they interfere with the *receiver* (node j). Thus

$$\mathcal{I}(e) = \{(k,\ell) \in \mathcal{E}_{ij} : j \in \mathcal{R}'_k\}. \qquad (6)$$

The descriptive names of these three cases are motivated as follows. The 01protocol model assumes that at most one link is active throughout the whole network (i.e., either 0 or 1 activation), clearly the most conservative reference case. The 11protocol model implicitly assumes that the IEEE 802.11 MAC [2] is employed (hence the name), whereas the 16protocol model tries to capture several less restrictive access control modalities, including the IEEE 802.16 MAC [13]. The IEEE 802.11 standard requests acknowledgement (ACK) for every transmission, thus the motivation for identically treating transmitters and receivers in the 11protocol model is that, when ACKs are sent, the logical receiver behaves as a physical transmitter, and vice versa. However, if the MAC does not follow the IEEE 802.11 standard, these assumptions may be too conservative. For example, the IEEE 802.16 standard differs from IEEE 802.11 in that a receiver can not cause disturbance, or conversely, there is no need for avoiding disturbance at the transmitter. The 16procol is also more appropriate for STDMA approaches to JRS where no ACK is used.

Finally, another approach, which should yet be considered as more realistic, uses the so-called physical interference model [4], [11], which evaluates the SINR at the receiver and compares it with a threshold γ that determines whether the transmission is successful. If the transmit powers are all equal to 1, this means that the requirement for a correct reception from i to j is

$$\frac{g_{ij}}{\sum_{\substack{k \text{ is an active}\\ \text{source of disturbance}}} g_{kj}} \geq \gamma\,, \qquad (7)$$

From the physical layer standpoint, this means that we approximate the error probability of the transmission, which is in general a decreasing function of the SINR, with a step function switching from 1 to 0 at γ. Note that the value γ can even be differentiated over the links.

In the context of formulating an integer linear program for the JRS, requirement (7) can be transformed, by using the transceiver constraint (3) into the following linear constraint:

$$\forall(\mathbf{ET}): \quad g_{ij} \geq \gamma \sum_{k \in \mathcal{S}'_j \setminus \{i\}} g_{kj} \Big(\big(\sum_{\ell \in \mathcal{R}_k \setminus \{j\}} x_{k\ell}(t)\big) + x_{ij}(t) - 1 \Big), \qquad (8)$$

where one can verify that, similarly to the artifice employed in (4), the constraint is trivially verified if $x_{ij} = 0$.

To sum up, several interference constraints can be chosen. They all involve a degree of freedom, i.e., the level of interference which can be tolerated by an active link. In the protocol models, this is the definition of the sources of disturbance, i.e., the set $\mathcal{E}'$ (usually based on geometric considerations). Moreover, there are multiple possibilities of implementing the protocol model itself (11protocol, 16protocol). In the physical model instead, the fine-tuning of interference effect is determined by γ. This does not mean that the choice of the interference model is irrelevant. It is actually the opposite, as many lower layer considerations indicate that the physical model may be preferable, besides offering the advantage of taking the cumulative behavior of interference into account.

V. Solution through Genetic Algorithm

To evaluate our ILP model, we do not choose any optimization function to couple with the constraints. Simply, we seek a feasible solution, if any exists, with a GA [9]. This means that we generate a *population* of candidate solutions, which at the first generation consists of random individuals. The solutions are ranked according to a fitness criterion explained in the following, so that the ones which score best have higher chances of surviving and generating offspring. The population evolves through generations until an efficient solution is found.

This evolution can be achieved only if certain constraint violations (or relaxations) are admitted. Actually, were we able to immediately find an individual respecting all the constraints, we would not need further iterations and the problem would be solved. A natural choice for the ranking function of the GA is to sort the candidate solutions related to how large their constraint violations are. However, this requires that constraints do not affect each other, else violations are counted twice. For this reason, we distinguish between the constraints according to whether they affect each other or not. For instance, the transceiver constraint is a necessary condition; if it is violated, comparative ranking becomes impossible, since the other constraints rely on the assumption that all nodes either transmit or receive to one other node. Thus, we assume that this condition has to be verified by any individual. If a solution generated as an offspring violates this constraint, it is immediately *repaired* [14]; to this end, we simply randomly de-activate all multiple edges causing the violations but one.

Conversely, interference and flow conditions are prone to be relaxed. In fact, individuals violating some interference conditions can still generate valid solutions. In this sense, we observed that it is better to admit some violations during the evolutive process, to increase the diversity of the "genetic material," even though solutions with invalid interference situations are ranked with a lower score. To implement this score penalty, we simply assume ideal error detection, which is sensible, as the scheduling is entirely centralized. So, transmissions causing violations of the interference condition, according to the constraint chosen among the ones in Section IV, produce an erroneous outcome and require to be retransmitted. Hence, a violation of the interference conditions reflects in the flow delivery.

For what concerns the flow constraint, we relax (2) so that the number of packets delivered to the sink at time T is the fitness criterion for the solutions to evolve. Ideally, the GA iterations end when the number of packets *not delivered* to the MAP equals 0. However, we also have the additional advantage, which will be exploited in the following, that our GA also allows to identify very good solutions (theoretically, the best possible ones) in the case there are not feasible individuals. Finally, we remark that GAs are well known to have an advantage in terms of computational complexity with respect to other sophisticated optimization techniques [9], [14].

We implemented our GA, introducing constraints and relaxations as previously discussed. As a protection against the risk of ending in a local minimum, the GA takes 5 independent populations of 500 individuals, which evolve for a maximum of 200 iterations. This choice of parameters has been empirically tested to always find the best solution in practice, with an acceptable computational effort (each execution takes always less than 180 seconds over a Pentium IV 3.2 GHz processor with 1 GB RAM).

VI. Performance Evaluation

We simulate a WMN built over a 3×4 grid of MRs, where grid segments measure 30 meters. The only MAP y is placed in a corner position. Any other MR i has an initial backlog $q_i(0) = 6$ packets. The time T spans from 10 to 28 time-slots. We generate 20 different instances where the propagation parameters are independently drawn. For all $i, j \in \mathcal{N}$, the link gain g_{ij} is determined with a path loss proportional to $d_{ij}^{-3.5}$, where d_{ij} is the distance between the nodes. Additionally, a shadowing term derived according to a two-dimensional version of Gudmundson model [15] with $\sigma = 5$ dB and correlation at 100 m equal to 0.6 is superimposed. Finally, r_{ij} is determined as a function of g_{ij}, as follows. We determine the ratio between g_{ij} and the gain at 1 m; if this is between α_i and α_{i+1} dB, then $r_{ij} = \rho_i$, where $\boldsymbol{\alpha} = (+\infty, -53, -60, -65, -70)$, $\boldsymbol{\rho} = (11, 5, 2, 1)$. If the gain is lower than -70 dB, there is no edge in $\mathcal{E}$. Finally, the interference criteria in the protocol models are assumed to be based on physical distance only. Nodes are included in sets $\mathcal{R}'_i$ and $\mathcal{S}'_i$ if their distance from i is less than 60 meters.

interference model	T			
	10	14	18	22
01protocol	0.00	0.00	0.00	0.09
11protocol	0.00	0.06	0.31	0.91
16protocol	0.00	0.47	0.94	1.00
physical, $\gamma = 5.0$	0.00	0.00	0.66	0.88
physical, $\gamma = 3.0$	0.03	0.44	0.78	1.00
physical, $\gamma = 0.0$	0.72	0.94	1.00	1.00

TABLE I
Fraction of feasible solutions found by the GA

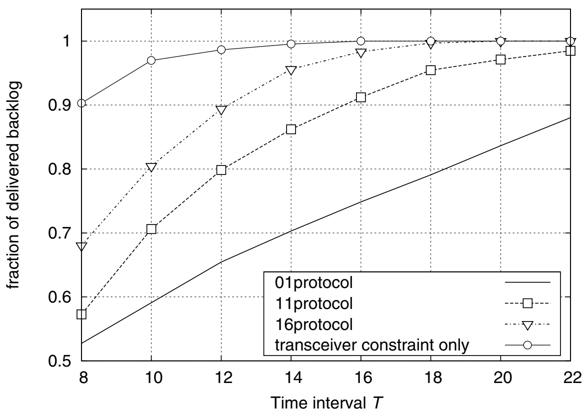

Fig. 1. Delivered traffic under the protocol models.

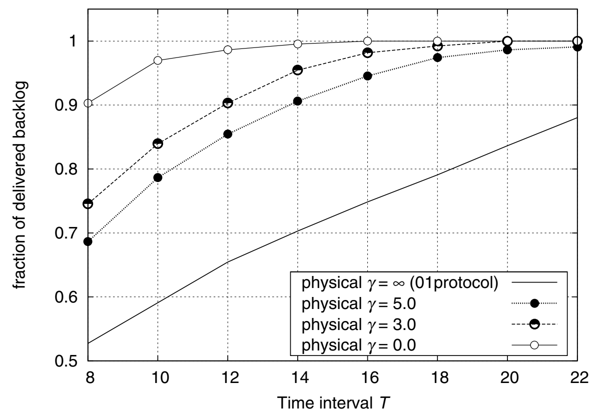

Fig. 2. Delivered traffic under the physical model with various γ.

Table I reports the fraction of feasible solutions found. The protocol models have very different performance, e.g., using the 01protocol model the problem can almost never be solved, whereas the 11protocol and the 16protocol models found more feasible solutions. The physical model performs differently according to the value of γ. For example, the choice $\gamma = 0$ corresponds to the best possible case of network parallelism (no interference constraint limits multiple transmission, only the transceiver constraint).

Figs. 1 and 2 report a more detailed analysis where the fraction of delivered load is considered instead, resulting from the relaxation of (2). Remember that the GA is able to find the most efficient solution even if the problem is unfeasible. Fig. 1 compares the protocol models. As a reference, we also plot the case where there is no interference constraint and only the transceiver constraint limits simultaneous link activations. The figure shows that the 01protocol is extremely conservative, but also the 11protocol model imposes serious limitations to the network parallelism. To mitigate them, one can adopt the 16protocol model. From the qualitative viewpoint, the protocol models have a similar trend, though re-scaled, which is a consequence of their pair-wise evaluation of interference. There is a significant gap between the 11protocol and the 16protocol model, so it is unclear how to avoid conservative limitations or conversely too optimistic assumptions.

Fig. 2 focuses instead on the physical model. The case with $\gamma \to \infty$ achieves the same performance of the 01protocol model, whereas $\gamma = 0$ is identical to the case with the transceiver constraint only; they similarly serve as comparison terms. With respect to the protocol model, the increase with T of the delivered traffic is more gradual, which is due to the fact that the cumulative effect of interference is more properly accounted for. Moreover, the parallelism decreases with γ. Actually, the physical model is more easily tunable in this sense, and the whole range from $\gamma = 0$ (the most optimistic possibility in terms of interference) to $\gamma \to \infty$ can be covered.

VII. Conclusions

The impact of interference on JRS is very strong and its correct characterization is key to perform network analysis. The choice of the interference model is often based on ease of implementation, from both theoretical and practical (i.e., inherently related to the MAC protocol under use) standpoints. However, the need for realism in the results should always be kept in mind. In particular, adopting the protocol model as it were perfectly reflecting reality may result in an undesirable lack of parallelism. WMNs are designed to provide good network coverage and high data rates in a network-wide sense, thus the more accurate characterization of the system obtained by utilizing the physical model may be preferable. Moreover, MAC protocols for WMNs should be engineered in order to take these aspects into account.

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