Chapter 6

Routing, Interface Assignment and Related Cross-layer Issues in Multiradio Wireless Mesh Networks

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Abstract Many technological standards for Wireless Mesh Networks include the possibility to use several nonoverlapping channels for data transmission. This represents an opportunity that can be exploited by equipping the terminals with multiple network interfaces. This opens up an interesting challenge, namely, how to simultaneously use different frequencies, so as to limit collisions and therefore activate multiple simultaneous transmissions in the same geographic area. At the same time, this poses new issues; for example, network connectivity is reduced, because nodes that do not interfere are also unable to communicate with each other. Thus, more complex interface management techniques are required. Moreover, a paradigm shift from the classic routing schemes is needed. Usual approaches are not always satisfactory because they often use shortest-path heuristic and tend to concentrate transmissions to certain nodes. To efficiently exploit the presence of multiple channels instead, a proper routing algorithm should avoid congested links and possibly make use of an estimation of the actual network traffic. Therefore, cross-layer information exchange can be useful for an efficient functioning of the routing protocols. In this chapter, we will analyze all these issues and propose and identify possible solutions.

6.1 Introduction

Wireless mesh networks (WMNs) [1, 2] are a network technology currently under development to provide end users with broadband wireless connectivity. In such systems, each mobile terminal owned by an end user, called mesh client (MC), is linked through a single radio hop to a mesh router (MR), a fixed infrastructure node. All the MRs are, in turn, interconnected to each other in a multihop fashion so as to

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form what is referred to as the network backbone. This kind of structure is easy to install because several low cost nodes can be added to improve the backbone connectivity. Moreover, MRs do not need to be battery-powered, because they can be easily placed in correspondence with a power outlet. Finally, the all-wireless structure does not require cable deployment, thus making WMNs appealing for connecting both vast rural regions and crowded urban areas where cable deployment is not cost-effective.

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. Therefore, they usually have better computational capabilities than the other MRs, which work as simple relay nodes; for this reason, it is sensible to think of MAPs as the centers of the network management operations. On the other hand, this determines a higher cost of such nodes and therefore their number is reasonably limited. In most cases, just one or two MAPs are used; this will be also the case for the examples discussed throughout this chapter.

Because the communication between a MC and its reference MR is single-hop, most of the challenges of the WMN management are at the backbone level. This part of the network is similar to other kinds of wireless multihop networks, such as ad hoc and sensor networks. Differently from them, however, the main problems in the inter-MR communication do not relate to mobility and energy saving problems, which are avoided because of the assumptions made above. Instead, other major technical issues arise especially when the network size grows (scalability problem). Among them, one of the most challenging is represented by routing [3]. In fact, the performance of WMNs in this sense is, similar to any other multihop network, limited by wireless interference. The placement of additional relay nodes yet mitigates the problem, because it gives additional opportunities for traffic forwarding; however, the performance improvement is often limited and does not linearly scale with the number of nodes. Thus, the design of efficient routing algorithms plays a key role among WMN research topics.

Moreover, WMN solutions are often thought as utilizing existing standards, such as IEEE 802.11 [4], without any modification. On the one hand, this enables to use off-the-shelf network cards for the wireless mesh nodes, which keeps the infrastructure costs low. On the other hand, a straightforward adaptation of existing technologies, without taking into account the specific purposes of WMNs, will result in an inefficient management. In fact, these standards are commonly used in a different context; in particular, IEEE 802.11 is used almost exclusively in a single-hop fashion, whereas its collision avoidance mechanism is known to suffer from several problems in multihop scenarios, such as the decrease of network parallelism because of the exposed terminal problem [5].

In general, a compromise shall be sought between this inefficient usage and the design of entirely new protocols. A possible solution, in this sense, can be the idea of finding new applications of possibilities already envisioned by the protocol but scarcely used in practice. An example where this concept can be applied concerns the possibility of exploiting multiple portions of the available wireless spectrum. For example, the IEEE 802.11a/b/g specifications provide multiple channels, some of which can be regarded, with a good degree of approximation, as nonoverlapping (specifically, 3 channels for IEEE 802.11b/g and and 12 channels for IEEE 802.11a).

There are two possible approaches to deal with multiple channels. In the majority of the literature, it is assumed that they are perfectly nonoverlapping; in this chapter we will consider this case only. There is also an interesting line of research, discussed in more detail in the following, where partial overlap of the channel is taken into account with the aim to exploit it [6]. However, this approach requires to entirely reformulate the routing problem. The case of perfect nonoverlap is simpler, because it allows to regard the routing problem as a multicommodity allocation or a graph coloring issue. Notice that models for studying networks exploiting frequency diversity date back before the success of wireless networks, because they were already investigated, e.g., for optical fiber networks [7].

Although multiple channels can be introduced, and actually they are already available in existing standards, terminals are typically configured to operate on a single radio channel: in fact, in a single-hop scenario, this frequency diversity is mostly introduced to avoid collisions from different networks. In a WMN case, instead, this feature can be used to increase the number of transmissions that can be exchanged within a neighborhood. This imposes to differently tune the Network Interface Cards (NICs) of the involved MRs.

The opportunity given by multiple nonoverlapping channels is better exploited if more than one NIC is available at a single node. In this way, one can avoid, or at least mitigate, the need for dynamically tuning to a common frequency the interfaces of MRs that are meant to communicate with each other. As will be discussed in the following, fast frequency-switching transceivers are in fact not always feasible. Actually, the cost decrease for commodity hardware makes multi-interface terminals economically sustainable, even though in general it is not possible, for many practical reasons to provide each node with a single NIC per every available channel. However, as shown in [8], the largest advantage in terms of network capacity, intended as traffic that can be transmitted over the network in a collision-free manner, is present already for a limited (though larger than one) number of NICs per node. The relative performance improvement when the number of interfaces approaches the number of available channels becomes marginal.

Thus, we will focus on multiradio, i.e., multichannel *and* multi-interface, WMNs. The investigations carried out in the following concern the strategy to determine the channels to which the NICs of every node shall be tuned, which can be regarded as a multiple allocation optimization problem, and how this affects routing strategies over the WMN.

There is a two-fold relationship between the routing and the interface assignment problems. First, when the routing algorithm is applied, two nodes i and j can communicate, and therefore it is possible to route traffic through a network link from i to j, only if they share a common channel assigned to at least one of their NICs. Conversely, to be realized efficiently, the interface assignment should take into account the routing pattern of the network. In fact, because the use of different channels decreases not only the mutual interference but also the network connectivity, it should leave the possibility of connecting the nodes along the main traffic routes and possibly decreasing the number of interfering links.

Classic routing protocols for multihop networks [9,10] may be easily extended to support multiple interfaces at each node. However, those protocols typically select shortest-hop routes, which may not be suitable for multichannel networks; as was noted in [11], routing metrics based on hop count only should be integrated by also taking into account the network load. Moreover, longer paths may be preferable if they allow to decrease interference and increase transmission parallelism. At the same time, more bandwidth should be given to nodes that support higher traffic, i.e., channels assigned to these links should be shared among a fewer number of nodes. More in general, the interface assignment strategy should be traffic-aware in the sense that it matches the distribution of traffic load in the mesh backbone.

For these reasons, in the following we will overview solutions presented in the literature and summarize basic criteria for routing and interface assignment in multi-radio WMNs, giving particular emphasis to the interaction between these two tightly related problems that can be efficiently managed with an adequate knowledge of the network traffic. In particular, we will discuss how to exploit the knowledge of the load on the links [12] and how to estimate it [13] and we give practical examples of application.

The rest of this chapter is organized as follows. In Sect. 6.2 we overview papers on routing and channel assignment in WMNs appeared in the literature. In Sect. 6.3 we give a comprehensive summary of different criteria that can be used to approach the problem. In Sect. 6.4 we formally state the problem and introduce definitions and notations. Section 6.5 describes a possible methodology to estimate the network load, which, as previously argued, is extremely useful to achieve a good cross-layer management of routing and interface assignment; additionally, it outlines an optimization framework for a routing-aware channel assignment problem, where load information is explicitly taken into account. Finally, the conclusions are drawn in Sect. 6.6.

6.2 Background

The problem of frequency selection in a multichannel networks inherits some approaches and methodologies, as well as the idea of using graph theory, from the problem of assigning channels in an optical network [7]. In this case however, the edges are fixed, because they correspond to a cabled connection between nodes. Thus, that topic resembles more closely the classic graph coloring problem. In the wireless case instead, the possibility of managing not only the frequency on which a connection is tuned to, but also the existence of the edge itself, requires an extended treatment. In this sense, another related problem is the frequency re-use planning in cellular networks, where graph representations have been also used [14].

An interesting line of research dealing with multichannel WMNs is based on the observation that most of the available channels are indeed partially overlapping. This, instead of being considered harmful, could be turned in an opportunity to achieve connectivity (though an imperfect one) in a less interference-prone way.

It is also possible to have a fully connected network and decrease interference while using a single NIC for all nodes.

Such an approach, investigated for example in [6] and [15], though very promising, implies to entirely reformulate the network management, and is therefore out of the scope of the present chapter, where we deal instead with adapting existing routing approaches to the multichannel case, and we consider different channels as perfectly separate in frequency.

Approaches for multiple orthogonal resource allocation mainly deal with time-division multiple access (TDMA), as for instance done by the earlier work reported in [16]. In fact, this paper proposes to introduce multiple time slots, with a special control slot where the users can rendezvous to negotiate the access in a distributed manner. However, this case can be easily extended, with few modification, to a frequency-division multiple access (FDMA) case. For example, [17] reports a description of the issues that need to be faced when dealing with multiradio multihop networks and proposes a similar strategy where a common control channel is used to coordinate a distributed assignment of multiple channels.

Because of the similarity between FDMA and TDMA multiplexing, some papers jointly investigate, together with routing, *both* channel assignment and packet scheduling over time [18–20]. In [18], the goal of finding a joint channel assignment, routing and scheduling technique that optimizes throughput of the MCs is studied. The problem is formulated as a linear programming (LP) framework. The approach used by this paper for tackling multichannel networks is similar to the one adopted in [21] where an analogous optimization framework is extended to the multichannel case. Under specific interference assumptions, necessary and sufficient conditions are described, under which collision free link schedule can be obtained. In particular, as done by most of the papers related to this topic, the protocol interference model is used, as introduced in [22]. This dictates to model interference through collisions, and can be equivalently mapped through a so-called *conflict graph*. Actually, such a model is not perfect, because it implies some approximations in modeling interference as pointed out, for example, in [23]. Nevertheless, it is quite simple and is, in fact, often used by those papers modeling channel assignment through LP frameworks. However, because the problem of achieving the optimal allocation of scheduling times over several frequencies is shown to be NP-hard, the final solution proposed by [18] is an efficient heuristic approach, which can be proved to be at most a given factor away from the optimum.

In [20] a similar problem of joint routing, channel assignment and scheduling is investigated, where the goal is again on throughput maximization. Interference is again modeled through a K-dimensional version of the protocol interference model. After that, the feasibility of a schedule is verified by means of a sufficient condition, that is considering whether the conflict graph can be properly colored, by using as many colors as TDMA slots so that conflicting edges are differently colored (i.e., they are active over different time instants).

Another similar optimization is also considered in [19]; to deal with the high complexity of the resulting problem, the solution is sought through Simulated Annealing [24], which is an evolutionary technique for LP problems offering a good trade-off between accuracy and computational complexity. The solution operates in two steps, i.e., the routing/channel assignment problem is split between two parts. First, routing is solved by means of a shortest-path strategy. Then, a simulated annealing algorithm tries to optimize the assignment of the NICs. Because this optimization technique needs a starting solution as input, channels are initially assigned randomly, provided that they satisfy interference constraints. Subsequently, the system evolves according to the simulated annealing procedure, which seeks to maximize the throughput.

An even simpler solution to overcome the NP-completeness of the problem is to propose efficient heuristic strategies. This methodology is adopted for example in [8, 25, 26]. In spite of their simplicity, these strategies can achieve good performance, especially in light of the fact that they do not need particularly complex computations. It is worth noting that, for the most, they employ the conflict graph model to represent interference, and therefore the proposed heuristic is related to graph coloring considerations.

All these approaches refer to a centralized solution, hence they assume the availability of a central controller (e.g., located in one of the MAPs) that takes care of solving the allocation problem and signalling the obtained solution to the other nodes. Instead, [12] proposes a decentralized maximization problem, where the interference constraints refer only to neighboring transmissions. An extended version, proposed in [15] by the same authors, investigates the case of partially nonorthogonal channels. This is done based on a technique in which a channel weighing matrix is calculated. An original aspect of this approach is that, even though interference is still based on the protocol model, or, equivalently, on conflict graphs, instead of simply preventing collision from arising at all, it is taken into account how they affect (i.e., degrade) the capacity of the links, which allows for a more tunable problem characterization.

6.3 Thoughts for Practitioners

In this section we review some practical criteria that have been proposed to determine interface assignment in multiradio WMNs. The technical contributions in this field are very heterogeneous for what concerns the depth of theoretical investigations. Thus, we try to discuss relevant points of interest that distinguish the existing proposals and we identify practical general criteria. The reported references can give further details on these topics.

6.3.1 Static vs. Dynamic Assignment

Interface assignment strategies can be classified according to the time-scale involved in the assignment, i.e., the rate of variability of the channel allocation.

Following [17], the schemes proposed in the literature can be divided into static and dynamic interface assignment. Hybrid schemes are also possible.

Within the static strategy, the interfaces are assigned with a constant value over time, or at least they are unchanged over a time period that is significantly larger than the packet scheduling time unit. The simplest possibility for a static assignment is the so-called common channel assignment (CCA), which was proposed in [25], actually more as a theoretical comparison scheme than a real policy. In CCA, the interfaces of each node are all assigned the same set of channels. For example, if each node has two radios, then the same two channels are used at every node. Hence, the connectivity of the network is the same as that of the single channel approach, possibly with redundant repetitions. Thus, there is still an advantage because multiple channels can be leveraged to increase throughput. However, the improvement achieved with respect to the single channel case is far below the highest potential gain of using multiple radios. Thus, varying channel assignment (VCA) strategies are usually proposed, where the variation is meant over space, not over time, as the assignment is still static, but allocates different sets of channels to different radio interfaces. VCA techniques are usually more efficient than CCA but have the potential risk of partitioning the network, and in general the length of routes between MRs increases.

In contrast, dynamic strategies allow all channels to be associated with any interface freely and continuously update the assignment that is potentially changed on a per packet basis. However, the challenge associated with this scheme is that whenever two nodes need to communicate with each other, a coordination scheme had to exist to ensure that they are on a common channel. For example, a common channel can be used as a rendezvous point to negotiate the allocation for the next transmission phase, as done in [27]. Another example is the slotted seeded channel hopping (SSCH) mechanism [28] in which each node switches channels synchronously in a pseudo-random sequence to allow all neighbors to meet periodically in the same channel.

The advantage of dynamic assignment [29], is the potential to exploit all channels with few interfaces. Their main problem relates to the demanding hardware requirements. In fact, real time services, which WMN are supposed to provide, have stringent delay requirements, which are therefore hardly met if the additional delay imposed by NIC switching time is introduced. Thus, these schemes have limited practicality unless expensive terminals are employed. Moreover, switching interfaces may result in a *deafness* problem, occurring when a node wants to communicate with another, which is tuned on another channel. Channel access issues arise, because the transmitter, being deaf, is unaware that the receiver may be busy in another transmission. This problem can be solved by introducing appropriate rendezvous on certain channels at certain time instants, and determines many challenges that are out of the scope of this chapter.

Finally, hybrid schemes apply a static scheme to some interfaces and a dynamic one for the rest. Examples of this kind are the link layer protocols described in [17] in which a VCA is used for the fixed interfaces. CCA may also be used for the fixed interfaces as is the case in the interference-aware channel assignment in [30]. In this case, there is certainty that any communication through some of the links can be established using the static part, but still the requirement of fast-switching NICs is present.

6.3.2 Centralized vs. Distributed Assignment

As any other resource allocation strategy, interface assignment schemes can be generally realized in centralized or distributed fashion. In the centralized schemes the channels are assigned by a central controller, usually located in one of the MAPs. In the distributed schemes, instead, each node assigns channels to its interfaces in a more loosely coordinated fashion, because no global network knowledge is available. Thus, the decision is based on neighborhood information. The complexity of this latter case is much lower, at the cost of lower efficiency. Especially, the effectiveness of distributed strategy is critical in relationship with routing awareness, which demands for network-wise knowledge.

In general, most of the techniques reviewed in this chapter are directly applicable within a centralized management. Extensions to distributed management are also possible, but they usually require information exchange to acquire some global knowledge at each node. Similar techniques to obtain a distributed implementation of routing and interface-assignment can be found for example in [8, 16, 29].

6.3.3 Heuristic vs. Optimization Strategies

As pointed out in Sect. 6.2, the joint routing and interface assignment problem can be investigated through a proper optimization framework, but the resulting complexity is very high. It is then possible to draw another classification of possible approaches, even though it does not relate to design aspects, but rather on practical methodologies to solve the problem. In fact, in the literature several papers investigate the problem through LP approaches [12,18,20,21], but also many contributions proposing a heuristic approach [17, 25, 26, 29].

From a general point of view, these two choices are extreme points of a tradeoff. LP solutions offer better accuracy, heuristics have lower complexity. Intermediate solutions are also possible, such as meta-heuristic techniques like Simulated Annealing, as proposed in [19]. However, we remark that these two possibilities are not perfectly separated. In fact, though LP approaches are usually limited to smaller WMNs and suffer from scalability problems, they can shed light on heuristic techniques in a more rigorous and appropriate manner. As a matter of fact, the aforementioned papers that give an LP formalization also investigate heuristic criteria to solve the problem inspired by the theoretical findings.

6.3.4 The Gateway Bottleneck

A practical criterion to assign channels to interfaces, useful especially for heuristic procedures, is to consider the MAPs at first, because during the execution of an algorithm the first nodes to receive an assignment can usually select the frequencies in a less constrained manner. In [31], where many inefficiencies possibly arising in WMNs are described, it was observed that the most congested nodes are likely to be the MAPs, where all the routes converge, a property referred to as *gateway bottleneck*. Also, the bottleneck is particularly limiting if a single gateway is present in the network; hence, it is suggested to always activate multiple MAPs (of course, this has beneficial effects not only in terms of network capacity, but also, e.g., in case of failure).

This implies that such nodes should be the ones where frequency diversity can be applied achieving the highest benefit. Especially if a single MAP is present, we could state a “rule of thumbs” of starting the channel assignment algorithm from it. Note also that in this case the property can be generalized, to some extent, by saying that the closer (in terms of number of hops) is a node to the MAP, the more critical can it be in terms of congestion. This is especially true for the node with the best connectivity to the gateway (e.g., in terms of highest rate, lowest interference, or both) among the neighbors of the gateway itself.

Actually, this strongly depends on the network topology. If the gateway has a single neighbor, the gateway bottleneck is simply translated to this node. On the other hand, if the network has a star topology, with all non-MAP nodes being neighbors of the gateway with relatively similar connectivity, there is no bottleneck whatsoever, or at least, no more than what dictated by the medium access control (MAC), because all multiple transmissions collide. However, in practical scenarios, the distance to the MAP in terms of number of hops can be a good heuristic weight to determine the priority in receiving a channel assignment. To some extent, this criterion is implicitly taken into account by certain existing heuristic algorithms [25,26].

6.4 Notation and Terminology

As done by many related contributions, we adopt in the following a graph-based representation of the WMN backbone. All terminals belonging to the backbone, i.e., all the MRs also including the MAPs, can be represented as *nodes* included in a set **N**. If two nodes can communicate, i.e., there exist conditions where they can exchange packets with sufficiently high success probability, we consider them as linked through a graph edge. This may require that all the other nodes in the backbone do not transmit, because the condition of successful transmission can be violated in the presence of interference from other nodes. For this reason, the existence of an edge is a necessary condition, but not a sufficient one, to have an error-free communication. In addition to the existence of an edge, also certain interference conditions must be verified, which may vary according to the interference model adopted. In this way, a notation is commonly achieved in many radio allocation problems, where the network is represented as a graph $\mathbf{G} = (\mathbf{N}, \mathbf{E})$, where the set $\mathbf{E} \subseteq \mathbf{N} \times \mathbf{N}$ contains the network edges. Note that, from the physical point of view, the edges in $\mathbf{E}$ should be *directed*. This means that, given $i, j \in \mathbf{N}$, $(i, j) \in \mathbf{E}$ does not necessarily imply $(j, i) \in \mathbf{E}$. Even though rarely taken into account, link asymmetry is very frequent in radio networks [32]. However, there are certain MAC protocols, most notably the IEEE 802.11 one, which explicitly assume the links to be bidirectional, e.g., for handshake exchange. In this case, it is implicitly assumed that nonsymmetric edges are discarded from $\mathbf{E}$. This is actually a nontrivial assumption, as argued in [33], but we take it since it is both simple and also very common in the literature. In the following, we will therefore refer to this case and take edges as bidirectional. Most of the reasonings can however be easily extended to more general scenarios where directed links are present as well.

We observe that the terminology used throughout the literature concerning graph representation of the network is rather assorted: the existence of an edge from i to j is also sometimes referred to as "j is within communication range of i" or "node j can hear node i." Even though these descriptions are not rigorous from the propagation point of view, as the radio transmission involves more parameters than just distance, they are often adopted in the exposition and we sometimes will use them as well. Similarly, notice that "topology" is a term often used as a synonym of "graph," in particular channel assignment seen on graph representations is often referred to as "topology control" problem.

In channel assignment problems there is an additional requirement for network representation, i.e., to describe radio interfaces, and whether they are tuned on the same frequency, otherwise no communication can occur between them. Note that interference conditions are entirely orthogonal to this latter issue, i.e., to exchange packets, two nodes must at the same time meet the requirement of having a shared NIC allocation *and* interference free communication.

Usually, to depict frequency allocation, the graph representation is split in two parts. In both of them, the set of nodes $\mathbf{N}$ is the same, but they differ in the set of the edges. In the first one, called *physical topology* $\mathbf{G}_\mathrm{P} = (\mathbf{N}, \mathbf{E}_\mathrm{P})$, the set of the edges consider all possible connections among nodes, with the only requirement of radio propagation. However, when the channels are assigned to the radio interfaces, it could happen that some nodes do not share a channel where to communicate, even though they are linked through an edge in $\mathbf{E}_\mathrm{P}$ (and therefore they can hear each other). To represent the network connectivity after the channel assignments have been determined, a *logical topology* $\mathbf{G}_\mathrm{L} = (\mathbf{N}, \mathbf{E}_\mathrm{L})$ is employed, where $\mathbf{E}_\mathrm{L}$ is determined by imposing the additional condition that only nodes sharing a common channel can be linked through an edge. Actually, because there may be nodes sharing *more than one channel*, there can also be *multiple edges* in $\mathbf{E}_\mathrm{L}$ linking the same pair of nodes. In this sense, $\mathbf{E}_\mathrm{L}$ is not strictly speaking a subset of $\mathbf{E}_\mathrm{P}$ because the channel graph may contain more than one element corresponding to the same edge in the physical topology. We also remark that the symmetry considerations previously made apply to both physical and logical topologies, because the property of sharing a channel assignment on a network interface is a symmetric property for any pair of nodes.

Moreover, we need a notation to specifically represent the channel assignment. If there are K orthogonal channels available, without loss of generality we can use the set of integers $\mathbf{K} = \{1, 2, \ldots, K\}$ to denote them. For all $i \in \mathbf{N}$, we denote with $\nu(i)$ the number of NICs owned by node i. The exact channel assignment is represented by an *interface allocation variable* denoted as y_i^q, where $i \in \mathbf{N}$ and $q \in \mathbf{K}$, which is a binary variable equal to 1 if node i has a NIC tuned on channel q and 0 otherwise. Note that $\sum_{r=1}^{K} y_i^q = \nu(i)$ for all nodes $i \in \mathbf{N}$. Similarly, if $i, j \in \mathbf{N}$ and $q \in \mathbf{K}$, we define a binary *channel edge variable* called x_{ij}^q and defined as equal to 1 if i can transmit to j using the q the channel, and 0 otherwise. If the link symmetry assumption holds, it is reflected in that $x_{ij}^q = x_{ji}^q$. These variables are connected through the relationship $x_{ij}^q = y_i^q \cdot y_j^q$.

An example of graph representation is given in Figs. 6.1 and 6.2, where the physical and the logical topologies, respectively, are shown for a sample network of six nodes with $K = 4$ channels. In this case, nodes a and f, which are shown to have wireline connection to the Internet, operate as MAPs, whereas the other nodes are ordinary MRs. For all nodes i, $\nu(i)$ is chosen equal to 2. In the logical topology (Fig. 6.2) the numbers written on the edges indicate the frequency on which they are established, and small numbers beside a node denote its NIC assignment.

First of all, the aforementioned difference between the two topologies can be observed. Some links of the physical topology can be absent in the logical topology, as is the case, e.g., for the edge (d, e). In Fig. 6.2, nodes d and e are not linked because they do not have a common interface assignment. On the other hand, all

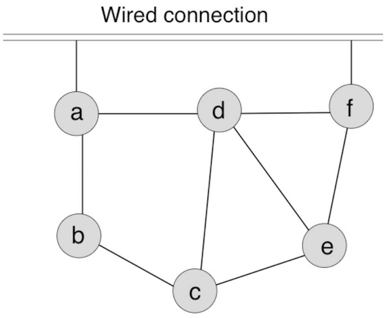


Fig. 6.1 1Physical topology of a sample network

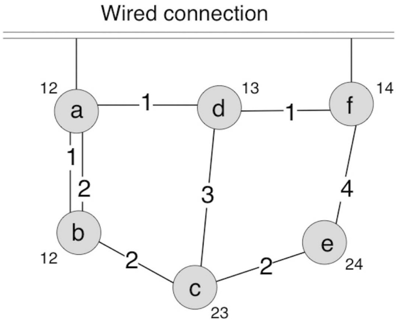


Fig. 6.2 Logical topology of a sample network

pairs of nodes in Fig. 6.1 are linked through one edge at most, whereas in Fig. 6.2 two edges connect nodes *a* and *b* because they share both of their interface assignment on channels 1 and 2.

By looking at Fig. 6.2, the interface allocation variables can be derived, for example $y_a^1 = y_a^2 = 1$, $y_a^3 = y_a^4 = 0$, or $y_e^2 = y_e^4 = 1$, $y_e^1 = y_e^3 = 0$. The channel edge variables are similarly determined, e.g., $x_{ab}^1 = x_{ab}^2 = x_{cd}^3 = 1$, $x_{ab}^3 = x_{ab}^4 = x_{de}^1 = 0$.

As discussed previously, in most of the investigations related to interface assignment, wireless interference is modeled through the so-called protocol model [22]. For our purposes this means that any edge $(i, j) \in \mathbf{E}_\mathrm{P}$ is associated with a set $\mathbf{J}(i, j)$, called *conflicting link set*, containing all the edges $(x, y) \in \mathbf{E}_\mathrm{P}$ whose activation on the same frequency than link (i, j) prevents a reliable transmission on it. For practical purposes, we adopt the convention of including also (i, j) in its own conflicting link set, i.e., $(i, j) \in \mathbf{J}(i, j)$, which simplifies the notation. The conflict relationship is mainly because of propagation phenomena; sometimes the conflicting link sets are defined based on simplified models, related for example to the distance between nodes. It is worth mentioning that this formulation is an abstraction useful for its conceptual simplicity, and for this reason will be used thereinafter. Yet, from the viewpoint of correctly modeling interference, more realistic descriptions, such as the so-called physical interference model [22] would be preferable. However, with some modifications, the reasonings presented in the following could be extended to alternative interference models as well. A detailed discussion about interference models is out of the scope of the present chapter. The interested reader can found overviews on this subject for example in [34, 35].

To instantiate the routing problem in the multichannel environment, we need also to define for all links $(i, j) \in \mathbf{E}_\mathrm{P}$ a parameter $c_{ij}^{(\mathrm{P})}$ that describes their *physical capacity*, i.e, their nominal data rate (e.g., expressed in Mbps). For completeness, we can introduce a value $c_{ij}^{(\mathrm{P})} = 0$ if $(i, j) \notin \mathbf{E}_\mathrm{P}$. According to whether edge (i, j) is reflected in the logical topology also, $c_{ij}^{(\mathrm{P})}$ will be mirrored into a *logical capacity* value. Because there are several channels, this latter value depends also on the channel q. Thus, for $i, j \in \mathbf{N}$ and $q \in \mathbf{K}$, we define $c_{ij}^{(q)}$ that can be larger than zero only if $x_{ij}^q = 1$.

Moreover, we denote with $\gamma^{(s,d)}$ the expected end-to-end traffic to be delivered from source s to destination d. Typically, in WMN either s or d will coincide with one of the MAPs. We also call $\lambda_{i,j}^q$ the amount of traffic (involving any pair source-destination) that passes through edge (i, j) over channel q. To put these quantities in relationship, it is useful to introduce a *binary routing variable* called $a_{i,j}^{(m,n),q}$ defined as

$$a_{i,j}^{(s,d),q} = \begin{cases} 1 & \text{if traffic from } s \text{ to } d \text{ is routed over } (i,j) \text{ on channel } q \\ 0 & \text{otherwise} \end{cases} . \qquad (6.1)$$

These variables will be put in relationship with each other in Sect. 6.5.3, where we use them to characterize traffic aware routing strategies.

6.5 Link Load Estimation and Traffic-aware Interface Assignment

The task of assigning channels to the available NICs can benefit from the exploitation of traffic information. In fact, because the purpose of utilizing multiple channels at the same time is to decrease interference and promote network parallelism, this should be done especially around the most congested links. In this section we discuss possible strategies to retrieve this knowledge and exploit it.

6.5.1 Link Load Estimation

There are different methods for deriving a rough estimate of the expected link traffic load. These methods depend on the routing strategy used (e.g., load balanced routing, multipath routing, shortest path routing, and so on). A possible approach is based on the concept of load criticality [13]. This method assumes perfect load balancing across all acceptable paths between each communicating pair of nodes. Let $P(s,d)$ denote the number of loop-free paths between a source-destination pair of nodes $(s,d) \in \mathbf{N} \times \mathbf{N}$, and let $P_l(s,d)$ be the number of them that pass through a given link $\ell \in \mathbf{E}_\mathrm{P}$. Then the expected traffic load Φ_l on link ℓ is calculated as

$$\Phi_l = \sum_{(s,d)\in E_\mathrm{L}} \frac{P_l(s,d)}{P(s,d)} \cdot \gamma^{(s,d)}. \qquad (6.2)$$

This equation implies that the initial expected traffic on a link is the sum of the loads from all acceptable paths, across all possible node pairs, that pass through the link. Because of the assumption of uniform multipath routing, the load that an acceptable path between a pair of nodes is expected to carry is equal to the expected load of the pair of nodes divided by the total number of acceptable paths between them.

Consider the logical topology as shown in Fig. 6.3 and assume that we have the three flows reported in Table 6.1.

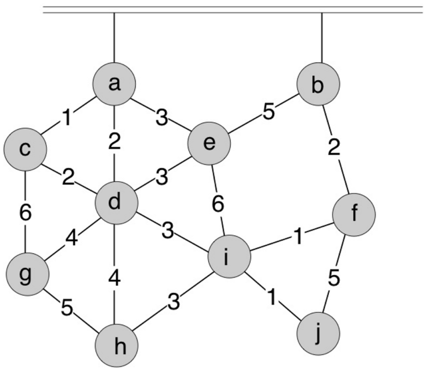


Fig. 6.3 Multichannel wireless mesh network

Table 6.1 Traffic profile with three flows

Source (s)	Destination (d)	$\gamma^{(s,d)}$ (Mbps)
a	G	0.9
i	A	1.2
b	J	0.5

Table 6.2 Possible flows between communicating nodes

(source, dest)	(a,g)	(i,a)	(b,j)
Possible paths	a–c–g	i–e–a	b–f–j
	a–c–d–g	i–e–d–a	b–f–i–j
	a–d–g	i–d–a	b–e–i–j
	a–d–c–g	i–d–c–a	b–e–i–f–j
	a–d–h–g	i–d–e–a	b–e–d–i–j
	a–d–i–h–g	i–d–g–c–a	
	a–e–d–g	i–h–d–a	
	a–e–i–h–g	i–h–g–c–a	
P(source, dest)	8	8	5

Because we have three different sources and destinations, we have

$$\Phi_\ell = \frac{P_\ell(a,g)}{P(a,g)} \cdot \gamma^{(a,g)} + \frac{P_\ell(i,a)}{P(i,a)} \cdot \gamma^{(i,a)} + \frac{P_\ell(b,j)}{P(b,j)} \cdot \gamma^{(b,j)}. \tag{6.3}$$

Furthermore, we calculate $P(s,d)$ for each flow. To this end, we need to determine all the possible source–destination paths, which can be achieved through a Route Discovery procedure [10]. Table 6.2 reports the results for the topology in Fig. 6.3. For practicality reasons, we have set an upper limit for the path length to 5 hops, e.g., by imposing a Time-To-Live to the Route Discovery broadcast packets.

From the above information, we can now calculate how many paths pass a specific link in the network topology. These values and the corresponding link traffic load Φ_ℓ calculated using (6.3) are shown in Table 6.3.

Based on these calculations, we can estimate the load between each neighboring node. The meaning of Φ_ℓ, which we have calculated throughout this example, is the expected traffic load of link ℓ, i.e., the amount of traffic expected to be carried over a specific link. The higher Φ_ℓ, the more critical the link. The idea is now to use this metric to decide which are the most congested points in the network, so as to assign possibly more than one frequency to heavily loaded links and fewer channels, or no channel at all, to less congested edges. Also, as Φ_ℓ can be seen as an estimated version, i.e., a measurement, of the the amount of traffic that passes through $(i,j) = \ell$, it holds

$$\Phi_\ell \approx \sum_{q=1}^{k} \lambda_\ell^q. \tag{6.4}$$

Table 6.3 Possible flows between communicating nodes

ℓ	$P_\ell(a,g)$	$P_\ell(i,a)$	$P_\ell(b,j)$	Φ_ℓ (Mbps)
a–c	2	3	0	0.675
c–g	2	2	0	0.525
c–d	2	1	0	0.375
d–g	2	1	0	0.375
a–d	4	3	0	0.9
g–h	0	1	0	0.15
d–h	1	1	0	0.2625
a–e	2	2	0	0.525
d–e	1	2	1	0.5125
d–i	1	3	1	0.6625
h–i	2	2	0	0.525
e–i	1	2	2	0.6125
b–e	0	0	3	0.3
b–f	0	0	2	0.2
f–i	0	0	2	0.2
i–j	0	0	2	0.2
f–j	0	0	2	0.2

Thus, if the variables λ_ℓ^q are available, they can be used in place of Φ_ℓ which depends on some a priori assumptions such as the perfect load balancing among the edges.

Moreover, several related issues open up. First of all, the strategy to weigh the different paths considers all of them as identical. Actually, there may be conditions that make a path less likely to be used for routing traffic, e.g., if it is very long. On the other hand, it is not true either that shortest hops are to be preferred. As discussed in [11], simple hop count may not be the most appropriate metric to decide on the best routes toward the destination. Thus, in general the determination of quantities $P(s,d)$ is a possible interesting subject for further research.

At the same time, the Φ_ℓ metric can be used only as a rough estimate of the load. Importantly, because channel assignment may affect how $\mathbf{E}_\mathrm{P}$ is reflected to $\mathbf{E}_\mathrm{L}$, there may be the case that some links are turned off by the absence of a common channel between the involved nodes. In this case, it is not possible to route traffic over them, and therefore the expected traffic load should be recomputed. Thus, also the study of these interactions and possible proposals about how to use similar metrics to infer where congestion is likely to arise are a possible challenging topic to investigate further.

6.5.2 Link Capacity Estimation

The link capacity, or the portion of channel bandwidth available to a link, is determined by the number of all physical links in transmission range of its transmitter or its receiver, i.e., in its conflicting link set, that are also assigned to the same channel. Obviously, the exact short-term instantaneous bandwidth available to each link is dynamic and continuously changing depending on several propagation and interference phenomena [13]. The goal here is to derive an approximation of the long-term bandwidth share available. Thus, the capacity $b_{ij}^{(q)}$ assigned to link (i,j) on channel q can be obtained using the following equation:

$$b_{ij}^{(q)} = \frac{\lambda_{ij}^{q}}{\sum_{(x,y)\in J(i,j)} \lambda_{xy}^{q}} \cdot c_{ij}^{(q)}. \tag{6.5}$$

Note that if $\nu(i) = \nu$, constant for all the nodes,

$$\sum_{q=1}^{K} b_{ij}^{(q)} \approx \frac{\Phi_{ij} \nu \cdot c_{ij}^{(\mathrm{P})}}{\sum_{(x,y)\in J(i,j)} \Phi_{xy}}. \tag{6.6}$$

In other words, the capacity share available to a link is approximately proportional to its expected load.

6.5.3 Traffic-Aware Joint Interface Assignment and Routing

Giving the preliminaries defined in Sect. 6.4 and the results reported previously, we may specify relationships among the variables that can be used, for example, in an LP context as done by [12]. We stress the important aspect that a comprehensive framework includes channel assignment (represented by variables y_i^q and x_{ij}^q), routing variables $a_{i,j}^{(m,n),q}$, and finally traffic information (variables $\gamma^{(s,d)}$). Thus, it is appropriate to refer to the resulting model as a traffic-aware joint interface assignment and routing. We focus on the model only, whereas the solution techniques are out of the scope of the present analysis. Only, we remark here that the model is rather general and can be solved in a plethora of ways, including exact and approximate, centralized and distributed ones.

The variables of the model are related as per the following relationship, which can be seen as LP constraints. The aggregate traffic on a given link depends on the routing variables and the traffic requirements, so that

$$\lambda_{i,j}^{q} = \sum_{(s,d)\in N\times N} a_{i,j}^{(s,d),q} \gamma^{(s,d)}. \tag{6.7}$$

The effective capacity $c_{ij}^{(q)}$ of link (i,j) on any channel q cannot exceed the nominal capacity $c_{ij}^{(\mathrm{P})}$ and it is zero if i and j do not share channel assignment q. Thus,

$$c_{ij}^{(q)} = x_{ij}^{q} c_{ij}^{(\mathrm{P})}. \tag{6.8}$$

Moreover, the aggregate traffic $\lambda_{i,j}^{q}$ must be less than $c_{ij}^{(q)}$. Actually, in [12] it is proposed to strengthen this constraint by including a parameter $\Lambda \leq 1$. The motivation is that perfect capacity sharing among all interfering links is not true in practice. Thus, this constraint may be ineffective because it overestimates the effective capacity. Obviously, this is just an artifice and other solutions to cope with this problem are possible as well. Then, we impose

$$\lambda_{i,j}^{q} \leq \Lambda c_{ij}^{(q)}. \tag{6.9}$$

Finally, we impose a constraint describing conservation of the flows, i.e.,

$$\sum_{\substack{j \in N \\ (i,j) \in E_{\mathrm{P}}}} \sum_{q=1}^{K} a_{i,j}^{(s,d),q} \gamma^{(s,d)} - \sum_{\substack{j \in N \\ (i,j) \in E_{\mathrm{P}}}} \sum_{q=1}^{K} a_{j,i}^{(s,d),q} \gamma^{(s,d)} = \begin{cases} \gamma^{(s,d)} & \text{if } s = i \\ -\gamma^{(s,d)} & \text{if } d = i \\ 0 & \text{otherwise} \end{cases}. \tag{6.10}$$

At this point, several metrics can be chosen as the metric to optimize. For example, following again [12], we can choose to minimize the ratio between load and available capacity share on the most congested link. This implies to optimize the utilization of the most congested link and results in the following objective:

$$\min_{(i,j) \in E_{\mathrm{P}}} \max_{x_{ij}^{q}=1} \frac{\lambda_{i,j}^{q}}{b_{ij}^{(q)}}. \tag{6.11}$$

This somehow determines a performance bound in terms of capacity, which is independent of the absolute values of load requirements $\gamma^{(s,d)}$. In fact, they can be rescaled until constraint (6.9) is violated. Therefore, the most congested link gives the capacity bottleneck for the throughput of the whole network. Of course, other objectives are possible as well, for example also introducing fairness considerations. Finally, once the objective function has been identified, the problem can be approached by both LP optimization frameworks and heuristic techniques, and both in a centralized and a distributed manner. The choice of the specific technique to use mostly relates to general design issues such as the computational capability of the terminals.

6.6 Directions for Future Research

Even though many algorithms have been proposed in this context, the design of efficient techniques for interface assignment and routing in multiradio WMN is still an open issue. In the previous sections, we have identified certain possible enhancements to the usual routing and channel assignment metrics. However, the research community need also to face the issue of implementing these techniques within an optimization framework.

In this context, two related problems appear to be of primary importance. First of all, *scalability* is known as the main challenge not only, e.g., for routing problems, but also for any resource allocation issue in WMNs. Because the impact of WMN is expected to be very pervasive, and it is often assumed that at least hundreds of nodes can be part of the network, we must acknowledge a difficulty in identifying practical algorithms for large networks. This involves the trade-off between exact solutions, whose computational complexity may explode as the number of variables (nodes times interfaces) can be extremely high, and heuristic techniques, which can often manage WMNs with many nodes but are very difficult to validate, because it is hard to tell how far from optimality they are. Moreover, another problem, which still relates to scalability issues, is to identify where the source of the computational capabilities is located, i.e., how to *coordinate* the mesh routers to achieve an efficient allocation. In this sense, another trade-off is involved, namely, centralized vs. distributed management. Centralized solutions can work only if the MAP is powerful enough and the number of nodes is not high, so that global awareness about nodes and channels is possible. Otherwise, distributed solutions should be sought. However, these techniques do not always achieve the same performance than centralized management.

For these reasons, it is key that new research on the topics of routing and interface assignment in multiradio WMNs involves a significant effort to determine efficient optimization techniques with low computational complexity, and also distributed implementations that approach the performance of centralized solutions. Moreover, we recognize the study of *clustered* networks [36] as a possible application of these principles. Aggregating terminals in small clusters that are easy to manage allow a dramatic reduction of the computational complexity. If the network partitioning is performend efficiently, the solution found is still close to the optimal. Finally, clustered managements of WMNs can be seen as an intermediate solution between the fully distributed (but also inefficient) and the fully centralized (with acute computational problems) approaches.

6.7 Conclusions

In this chapter, after having classified existing proposals according to their diverse characteristics, we have highlighted the motivations that suggest the benefit of using traffic aware channel assignment. This point has been further explored by presenting examples on how link load and capacity can be estimated, and this knowledge can be exploited.

We emphasize the importance of the interactions between interface assignment and routing for the capacity performance of multichannel WMNs. Routing and interface assignment can benefit from simple information passing, where the two layers are still separated but cooperating. Moreover, if the terminal capabilities allow for it, one can also think of merging together the related strategies with a cross-layer approach.

To sum up, from a general viewpoint there are strong expectations about multiradio WMNs providing end users with high network capacity. However, routing and interface assignment, require a careful, and possibly joint, investigation because of their tight interdependencies. Traffic aware algorithms, which offer the opportunity to turn this relationship to an advantage, appear as very promising to make this goal easier to reach.

6.8 Terminologies

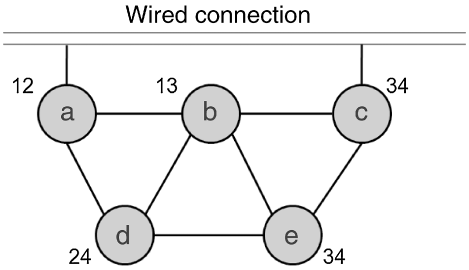
1. *Wireless mesh network (WMN)*. It is a communication network, where clients are connected via radio to routers that are in turn interconnected via multihop wireless links. Its structure is entirely wireless, thus making WMNs especially applicable where cable deployment is difficult or too expensive. Because the wireless medium is intrinsically broadcast, the radio nodes belonging to the WMN need special procedures to work in harmony with each other and enable dedicated communications.
2. *Mesh router (MR)*. It is a wireless element of a WMN that does not generate traffic but only serves to relay the traffic of the clients and convey it to a gateway (or vice versa). Actually, the structure of a WMN comprises multiple MRs that are interconnected with each other, so as to create a multihop wireless backbone. As communications over the backbone are limited by wireless interference, special techniques can be used to decrease the mutual interference of MRs, such as making them operate on different frequencies.
3. *Mesh access point (MAP)*. It is a special Mesh Router that is also connected to other external networks, e.g., the Internet, typically through a cabled connection. It can be therefore considered as a gateway for the network. However, because of the wireless structure, it also becomes a critical point for the routing, because of the so-called *gateway bottleneck* phenomenon. Indeed, the usual congestion caused by the convergence of the routes at the gateway is complicated by the fact that, as for any other node, interference can block some of the communications. Thus, its role in the WMN has to be carefully planned.
4. *Network interface card (NIC)*. Also called network adapter, it is the hardware component that enables the communication over the network. It involves both PHY (physical) and MAC layer capability. In particular, we are concerned in this chapter with NICs providing access over a wireless channel. Thus, a node can be supplied with multiple NICs to enable simultaneous communications on different channels, which is a way to avoid wireless interference.
5. *Topology*. Multihop networks are often represented as a graph, where the vertices are the MRs and the edges are the communication links among them. In this context, “topology” is often used as a synonym of “graph.” However,

when multiple frequencies are introduced, different graph representations (and therefore, different topologies) need to be considered, where the set of vertices, i.e., the MRs, is always the same but the set of edges changes.

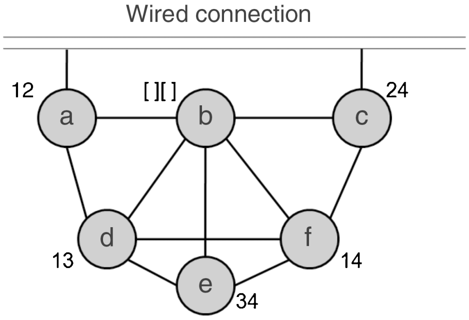
6. *Physical topology*. The *physical topology* corresponds to a graph representation of the multichannel WMN where an edge is drawn between two nodes if it is theoretically possible for them to communicate. This requires, of course, that the nodes communicate on the same frequency and wireless interference is absent. The physical topology corresponds to a graph representing the potential connectivity before any channel assignment procedure.
7. *Logical topology*. The *logical topology* depicts the connectivity of the WMN after a specific interface assignment procedure, so that any edge of the logical topology is kept only if the transmitter and the receiver actually share an NIC tuned on the same channel. If all the NICs are tuned on the same channel, the logical topology is equal to the physical topology. However, in general, the logical topology is different, for even multiple links are present between two nodes if more NICs tuned on the same channels can connect them. Alternatively, a link of the physical topology may be absent in the logical topology if there is no pair of NICs at both nodes with the same channel assignment.
8. *Wireless interference models*. According to the most common classifications, wireless interference models fall under two main classes: *protocol* and *physical* interference models. Protocol interference models describe interference as a binary relationship, i.e., two links either interfere or do not interfere with each other. Physical interference models take a more detailed approach with considerations taken from the physical layer. The most common version of the physical model corresponds to evaluate the Signal-to-Interference Ratio at the receiver, and check whether this is above a given threshold describing correct reception. Note that this also allows nonbinary evaluation of interference.
9. *Conflicting link set*. In the protocol interference models, each link $e = (i, j)$ is associated with its conflicting link set $\mathbf{J}(e) = \mathbf{J}(i, j)$, containing all the links whose simultaneous activation with e is forbidden (the protocol interference model describes interference as a binary relationship). In other words, if a transmission is taking place on any link belonging to $\mathbf{J}(e)$, e has to either stay silent or use another frequency, and vice versa. Otherwise, interference will destroy the communication.
10. *Load criticality*. A useful criterion to allocate channels is to exploit frequency diversity to alleviate network congestion. This can be achieved by allocating more different channels to *critical* links of the network. To this end, a possible approach requires at first to estimate the expected load Φ_ℓ for any edge ℓ of the physical topology. To this end, it is possible to use a simple a priori assumption such as uniform distribution of the end-to-end traffic over all possible paths, or perform measurements of the per-hop load. After this evaluation, channels may be assigned to fairly subdivide the expected load over all links, e.g., by minimizing the load on the more critical edge.

6.9 Questions

1. Determine the logical topology for the physical topology shown in the picture below.

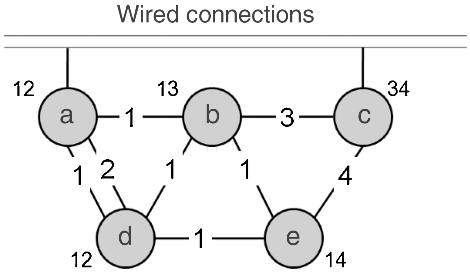


2. Consider the physical topology reported in the figure below. Channel assignment has been performed for all nodes but node *b*, which has two NICs. How can these two interfaces tuned so that every edge of the physical topology corresponds with at least one edge in the logical topology?



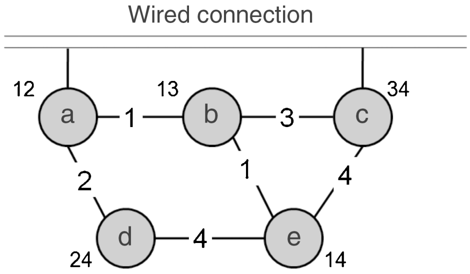
3. Discuss pros and cons of the dynamic channel assignment approach.
4. What is the "gateway bottleneck" and what does it imply, both in terms of limitations and practical approaches?
5. Consider a 7-node physical topology $\mathbf{G}_\mathrm{P} = (\mathbf{N}, \mathbf{E}_\mathrm{P})$, i.e., where $|\mathbf{N}| = 7$. Assume all nodes have three NICs and the network is fully connected, that is, there is an edge between any two nodes in **N**. Further, assume all links are symmetric and bi-directional. Determine:
   (a) The number of edges $|\mathbf{E}_\mathrm{P}|$ in the physical topology.
   (b) The number of edges $|\mathbf{E}_\mathrm{L}|$ in the logical topology that results from CCA, i.e., the same channel for all NICs even belonging to the same node.
   (c) The number of edges $|\mathbf{E}_\mathrm{L}|$ in the logical topology that results from a channel assignment procedure imposing the same triplet of different channels (say, (1,2,3)) for the three NICs belonging to any node.
   (d) The number of edges $|\mathbf{E}_\mathrm{L}|$ in the logical topology that results from a channel assignment procedure where five nodes have their NICs set to (1,2,3) and two nodes have their NICs set to (1,2,4).

6. Consider the logical topology reported in the figure below.



For every $i, j \in \mathbf{N}, q \in \mathbf{K}$, determine the interface allocation variables y_i^q, and the channel edge variables x_{ij}^q.

7. Consider the logical topology reported in the figure below.



Determine all the loop-free paths between a and e, called $P(a,e)$, and between c and d, called $P(c,d)$.

8. Consider the same logical topology of Question 7. Assume two flows are present in the network: from a to e, with expected end-to-end traffic $\gamma^{(a,e)} = 1.8\,\text{Mbps}$, and from c to d, with expected end-to-end traffic $\gamma^{(c,d)} = 1.5\,\text{Mbps}$.
According to the load criticality method with uniform traffic repartition over all paths (see Sect. 6.5.1), determine the expected load on each of the links below.

9. Consider a pair of nodes i, j whose conflicting set $\mathbf{J}(i,j)$ includes, beyond (i,j), the following edges of the physical topology: $e_1, e_2, e_3, e_4, e_5, e_6$. In the logical topology e_1, e_2, e_3 are tuned on channel 1, e_4, e_5 are tuned on channel 2, and e_6 is tuned on both. Assume that $c_{xy}^{(\mathrm{P})} = 10\,\text{Mbps}$ for any x, y.
Traffic is 2.0 Mbps between i and j, and as reported below on edges e_k.

Index k	1	2	3	4	5	6
Load of e_k on channel 1	3.0	1.2	0.8	0	0	1.0
Load of e_k on channel 2	0	0	0	2.4	1.1	2.0

Assuming fair bandwidth share, determine $b_{ij}^{(q)}$ for $q = 1, 2$ in the following cases:

(a) Nodes i and j share one NIC assignment on channel 1.
(b) Nodes i and j share one NIC assignment on channel 2.
(c) Nodes i and j share two NIC assignments on both channels 1 and 2, and the traffic is equally split between the resulting two links in the logical topology.

10. Consider the same setup of Question 9 (point (c)) but now assume we want to take the objective of optimal utilization into account, as per (6.11). Assume link (i, j) is the most critical of the network. How should its traffic be split between channels 1 and 2?

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