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Abstract

New multimedia services and ubiquitous networking pose great challenges on existing access network infrastructures. To cope with such requirements new access technologies, such as the fiber-wireless (FiWi), are being developed. Together with the emergence of new access networks, efforts are being made to reduce the amount of energy required to provide services. Indeed, this issue plays an increasingly important role. Here we propose an energy efficient routing algorithm for FiWi access networks. The main idea is to exploit the multipath capabilities of the wireless mesh front end of FiWi access networks to create energy efficient routes that optimize the sleeping and active periods of all ONUs and wireless nodes. To achieve this goal, an energy efficient network model based on network formation game theory is used. This model allows several network formation processes to be compared in regard to the energy efficiency of the routes they generate. Our results reveal that the farsighted network formation process establishes the most energy efficient routes, meaning that the choices done by this formation process were the best ones. However, this farsighted process is computationally expensive. For this reason a heuristic algorithm is developed, which explores the most energy efficient choices taken by the network formation processes, and farsighted process in particular. Results show that the proposed heuristic is able to obtain results close to the farsighted process.

Keywords: FiWi access network, energy efficiency, routing, network formation game theory.

1. Introduction

Communication infrastructures have, nowadays, a leading role in the reduction of the worldwide energy consumption, so that environmental goals and cost savings can be met [1, 2]. In these infrastructures, most of the energy is consumed at the access section, where new technologies have been proposed to fulfill the growing demand for bandwidth and ubiquity [1]. One of such technologies is the Fiber-Wireless (FiWi) that, as the name suggests, uses both optical and wireless technologies.

Two main research lines on FiWi access networks have been recently explored by the research community: radio-over-fiber and radio-and-fiber [3]. In radio-over-fiber, the light is modulated by the radio signal and then transmitted over the optical fiber, while in radio-and-fiber networks the optical and wireless networks are separate and protocol...
translation must be done. This article will focus on radio-and-fiber networks and, from here onward, the term FiWi access network will be used when referring to radio-and-fiber networks. FiWi access networks, depicted in Fig. 1, are comprised of a back end, where optical links are brought from the central office (CO) to some place near the users, and a front end, where wireless technology is used to provide Internet access to users. The most common optical network technology at the back end is the passive optical network (PON), which basically consists of a point-to-multipoint topology where one optical line terminal (OLT) at the CO is connected to many optical network units (ONUs) near the clients. Only a passive splitter, consuming no energy, is used between the OLT and the ONUs to broadcast the downstream signal to all ONUs and combine the upstream signals toward the OLT, synchronized in a TDM fashion to ensure a collision free medium. Of all the existing access network technologies, the PON is the most energy efficient because its high bandwidth is provided by a shared optical medium with no active devices between the OLT and the ONUs [1, 3, 4]. Nevertheless, energy efficiency can still be improved in PONs. This is so because downstream traffic is broadcast to all ONUs, which spend most of their time and energy receiving and discarding traffic that does not belong to them. This is not an efficient behavior and each ONU should be put to sleep when the traffic is not destined to it [5, 6]. To address this issue, energy efficient standards have already been developed that enable ONU transceivers to enter sleep mode [7]. Moreover, algorithms and methodologies have been proposed to decide when and for how long transceivers should be put to sleep [5, 6].

At the front end, wireless nodes, scattered throughout an area, provide Internet access to clients connected to them. The connection with the back end is done through Mesh Portal Points (MPPs), also known as gateways, having an interface to communicate with an ONU and another interface to communicate with Mesh Access Points (MAPs). Any
wireless technology can be used, as well as any topology. Here, the focus will be on the wireless mesh topology due to its cost effectiveness, bandwidth efficiency, wide coverage, high flexibility and scalability [3, 4]. Moreover, mesh topologies provide great routing flexibility, which can be exploited to improve energy efficiency. For instance, routes longer than the shortest ones can be used in order to increase sleeping periods throughout the network.

In this article, an energy efficient routing algorithm is proposed for FiWi access networks that optimizes sleeping and active periods of all ONUs and all wireless nodes in an integrated manner. To achieve this goal, network formation theory is used. Network formation is a field of game theory that studies the establishment of connections and formation of groups among players in order to improve their value [8]. In our case, every wireless node is a player establishing and severing connections with its neighbors in order to achieve the most energy efficient routes. The steps toward the development of this algorithm will be: i) appropriate definitions for network efficiency and stability; ii) development of a network model; iii) application of formation processes to the developed model in order to obtain insights on how energy efficient routes can be created, and where in the network it is more likely that route changes will produce improvements in energy efficiency; iv) development of a heuristic algorithm, having insights from the previous step as a basis. The model and definitions presented at the first two steps are based on the ones introduced in [9], while the remaining work comprises the contributions of this article.

The rest of this article is organized as follows. Section 2 presents a state of the art on energy efficiency applied to PONs, wireless networks and FiWi access networks. Then, FiWi access networks under study are presented in Section 3, along with some network formation theory concepts. A network game model is presented in Section 4, while in Section 5 network formation processes are applied to this model. In Section 6, the developed heuristic algorithm is presented, simulated and analyzed. The article ends with conclusions in Section 7.

2. State of the Art

Traditionally, communication networks have not been developed with energy efficiency in mind. However, due to the newly importance of energy consumption, the research community began recently to focus on energy efficient networks and access networks in particular, where most of the energy consumption in communication networks occurs [1, 2]. FiWi access networks, as aforementioned, are composed of optical and wireless technologies, meaning that its energy efficiency depends on how efficient both these technologies are and how well integrated they are. In the following three subsections, the state of the art on energy efficiency in optical, wireless and FiWi networks is presented.

2.1. Energy Efficiency in Passive Optical Networks

The PONs are already, by default, the most energy efficient access network infrastructures because the optical medium is shared among several ONUs and, moreover, only a passive splitter that consumes no energy is used between the CO and the ONUs [2, 1]. Nevertheless, significant improvements are still possible. More specifically, ONUs spend most of their time receiving and discarding traffic addressed to other ONUs, because downstream traffic is broadcast to all ONUs by the passive splitter. In this sense, putting ONUs to sleep whenever there is no traffic destined to them would certainly improve energy efficiency. In fact, current proposals have mainly focused on putting ONUs to sleep in a coordinated manner [5, 6, 7, 10, 11].

It is important to consider that ONUs, when waking up, take some time to synchronize with the OLT. Reducing this synchronization time is also a way of increasing energy efficiency. In [5], novel ONU architectures are proposed and analyzed that are able to reduce synchronization time from 5.125ms down to 125μs.

In [6], an energy management mechanism to synchronize sleep periods, which is compatible with IEEE 802.3ah, is proposed. This mechanism, in particular, matches downstream and upstream time slots, allowing ONUs to have more effective awake periods and longer sleep periods. Note that waking up an ONU also consumes energy and some time is needed for synchronization with the OLT. Hence, if the ONU wakes up less often to send/receive traffic, it will become more efficient. Through simulation, it is shown that, with this scheme, ONUs are able to stay awake just 10% of their time, in case of low traffic load, and 65% for higher traffic load. This scheme was then improved in [10] through the introduction of sleeping windows that increase and decrease according to traffic load.

1 Other than wireless sensor networks.
In [11], a combination of cyclic sleep function and adaptive link rate is used. The sleeping cycles vary according to the inter-arrival time of frames in order to maximize sleeping without harming QoS. In addition, an adaptive link rate is used to reduce power consumption in the presence of low traffic rates.

To support these newly developed methods, four energy saving modes have been introduced in the Gigabit-capable PON (GPON) standard [7]. Those modes are deep sleep, fast sleep, power shedding, and dozing, which differ on which modules are turned off and for how long.

### 2.2. Energy Efficiency in Wireless Networks

In wireless networks, many techniques have been explored across all layers of the protocol stack to improve energy efficiency [12]. In the physical layer context, improving energy efficiency is related to finding the right trade-offs between energy efficiency, spectrum efficiency, bandwidth utilization, and transmission power [13]. For instance, in [14], the trade-off between spectrum efficiency and energy efficiency in multi-cell scenarios with inter-cell interference is studied and it is shown that the power generated by neighboring cells reduces the achievable energy efficiency.

At the Medium Access Control (MAC) layer, the method used to access the medium can greatly influence energy efficiency. For instance, in collision avoidance methods, collisions can still be frequent, leading to retransmission of packets that may have already traveled through several hops and, hence, inefficient use of resources. To solve that, the use of strategies based on reservation and scheduling can be used instead of collision avoidance ones [12, 15, 16].

At the network level, intelligent routing and queuing methods can be used to prevent congestion that can lead to packet drops and retransmissions [12]. In the specific case of wireless mesh networks, if power from the grid is used, paths can be planned in order to optimize overall sleeping periods and overall energy efficiency. On the other hand, if batteries are used, paths can be planned in a way that energy depletion is distributed throughout the network, increasing network lifetime and avoiding network partitioning. In [17], a routing metric is developed that is able to reduce the cost per packet by 5% – 30%, when compared to shortest path routing, as well as increase network lifetime.

As for the transport layer, focus has been more on end-to-end connectivity and flow control. The traditional flow control of Transmission Control Protocol (TCP) does not distinguish between losses due to wireless link errors and losses due to congestion, which can lead to unacceptable delays [12, 18]. To overcome this limitation, in [19], an error recovery mechanism based on the coordination of TCP and IEEE 802.11 MAC protocol is proposed. This enables TCP to actually distinguish between transmission and congestion losses, improving its efficiency.

### 2.3. Energy Efficiency in FiWi Access Networks

Energy efficiency mechanisms in FiWi access networks have to take into consideration the capabilities of both optical and wireless technologies in an integrated manner in order to achieve overall energy efficiency. For instance, in a FiWi access network with a wireless mesh at the front end, a route longer than the shortest path can be used in order to maintain some transceivers in sleep/standby mode and use the remaining capacity of the other transceivers that are not in sleep/standby. Although some devices might end up consuming more energy than others, the objective is that the overall network energy consumption is reduced. Many of the studies discussed next assume that wireless nodes (MAPs and MPPs) are not mobile, since they are part of the access network structure, and therefore can receive electricity from the grid.

Proposals to improve energy efficiency in FiWi access networks are still scarce. A mathematical formalization and an efficient algorithm to schedule sleep and awake periods at every node of the FiWi access network was developed in [20]. In [21], a routing approach is proposed that tries to maximize the number of sleeping ONUs, forcing traffic to be rerouted toward the set of awake ONUs. This approach does not take into consideration fast sleeping periods when choosing the best routes, i.e. nodes are either on or off for long periods of time (hours). In [22], a QoS aware energy efficient routing algorithm is proposed. Similarly to [21], the objective is to minimize the number of awake ONUs. Fast sleeping periods were also not considered by the routing algorithm when choosing routes. In our approach, fast sleeping periods are taken into consideration and routes are established in order to optimize transmission and sleep periods of wireless nodes and ONUs in the most efficient way.

### 3. FiWi Access Networks

FiWi access networks are a hybrid of optical and wireless technologies proposed with the aim of supplying the bandwidth and ubiquity required by emerging services. From all the topologies that have been proposed for the front
end, the wireless mesh is deemed to provide cost effectiveness, bandwidth efficiency, wide coverage, high flexibility and scalability [4]. Moreover, a careful choice of paths at the front end can lead to an overall energy efficiency improvement. In this article, the focus will be on FiWi access networks with a mesh front end, as illustrated in Fig. 1.

The following notation will be used throughout this article:

- \( O \): Set of ONUs.
- \( G \): Set of MPPs. These nodes serve as gateways between the wireless and optical environments.
- \( R \): Set of MAPs. These nodes route traffic throughout the front end section.
- \( W \): Set of wireless nodes. This includes both MPPs and MAPs, \( W = G \cup R \).
- \( N \): Set of nodes in the FiWi access network, \( N = O \cup W \).

Every MAP must be associated with an MPP in order to send/receive traffic to/from the Internet. Thus, each MAP will establish an uplink wireless connection leading to its MPP, allowing traffic to be delivered through the use of one or more intermediate nodes. In this process, tree topologies emerge if every source node, and corresponding intermediate nodes involved in the forwarding process, are associated with the same MPP, as illustrated in Fig. 2. It is assumed that each of these tree structures has a single ONU, which is always the root. The descendants and ancestors of a node \( i \) are represented by \( \Gamma_i^+ \) and \( \Gamma_i^- \), respectively. Every node will have to forward traffic from its directly connected clients, called local traffic in this article, and traffic from clients connected to wireless nodes in \( \Gamma_i^+ \), called foreign traffic.

### 3.1. Network Formation

The just mentioned formation of tree structures resembles cooperative games, where players form coalitions in order to improve their outcome. However, coalition game theory considers only the set of players involved, while in our case the connections established between players are important, i.e. who is connected to whom. Network formation theory addresses such kind of formation, examining which players are part of each group and connections established inside a group [9].

In the following discussion, every wireless node, \( i \in W \), is a player trying to establish the best wireless connections in order to obtain energy efficient routes. In accordance with existing literature on network formation theory, the term component will be used from here on when referring to a group of players with established connections among them (tree).

**Definition 1 (Component).** A component is a group of wireless nodes/players where, for any combination of two of its elements \( i \in W \) and \( j \in W \), \( i \neq j \), it happens that \( [i] \cup \Gamma_i^+ \) \( \cap \) \( [j] \cup \Gamma_j^- \) \( \neq \emptyset \).
This definition is adapted to the nomenclature used in this article and to the independent network structures used. Also, it assumes that lone MPPs, i.e. MPPs that at the time are not included in any route used by MAPs, have their own component, contrarily to the definition in [8], which states that lone players are not part of any component. The reasoning behind this decision is that in network formation literature, it is considered that lone players have no effect on the well being of the network, whereas in our case, the MPP is still able to forward its local traffic and consumes energy, since it is directly connected to an ONU.

A connection established between wireless nodes \( i \in W \) and \( j \in W, i \neq j \), is denoted by \( ij \). The set of all the established connections form a network \( g \), and the set of all possible networks is represented by \( G \). Each network \( g \in G \), as a result of the established connections, has its own network value that can be calculated using a value function.

**Definition 2 (Network Value).** The network value is the worth that a network yields based on its connections. Such value is calculated using a value function of the type \( \Gamma : G \rightarrow \mathbb{R} \).

For the problem addressed in this article, the network value will measure the energy efficiency obtained by the established routes. Therefore, the objective is to reach a network \( g \in G \) with the highest possible network value. Such network will be termed efficient network.

**Definition 3 (Efficient Network).** A network \( g \in G \) is efficient if \( \Gamma (g) = \Gamma (g'), \forall g' \in G \).

A network value is a common value that may be distributed among players, wireless nodes in our case. This is done by means of an allocation rule.

**Definition 4 (Allocation Rule).** An allocation rule is a function \( v : G \rightarrow \mathbb{R}^W \), such that \( \sum_{i \in W} v_i (g) = \Gamma (g) \), where \( v_i (g) \) is the allocation value assigned to player \( i \in W \).

Every wireless node will try to improve its allocation value as much as possible by carefully establishing and severing wireless connections. This will be done by fulfilling some network formation process, discussed in the following section. When no player is able to increase its allocation value, following such network formation process, then the network is said to be stable.

**Definition 5 (Stable Network).** A network \( g \in G \) is stable when no player is able to improve its allocation value.

Stability has been modeled in many different ways in the network formation literature [8]. However, those stability models allow stable networks to have unconnected players. Such situation is not desirable for the problem addressed in this article because it would allow the existence of unconnected MAPs, which would not be able to send/receive traffic. Here, the stability notion termed complete connection stability, presented in [9] and also used in the context of FiWi access networks, is more adequate.

**Definition 6 (Complete Connection Stable Network).** A network \( g \in G \) is complete connection stable if all the following conditions hold:

1. for all \( i \in \mathcal{R} \), there exists one path \( n_1, n_2, \ldots, n_K \) such that \( \forall k \in \{1, \ldots, K - 1\}, n_k n_{k+1} \in g, n_1 = i \) and \( n_K \in \mathcal{G} \).
2. for all \( ij \in g \) and all \( z \in \mathcal{W} \):
   (a) \( v_i (g) \geq v_i ([g \setminus \{ij\}] \cup \{iz\}) \) and \( v_j (g) \geq v_j ([g \setminus \{ij\}] \cup \{iz\}) \).
   (b) \( v_j (g) \geq v_j ([g \setminus \{ij\}] \cup \{iz\}) \) and \( v_i (g) \geq v_i ([g \setminus \{ij\}] \cup \{iz\}) \).

The complete connection stability dictates through condition 1 that every MAP has one uplink wireless connection that leads to an MPP. Also, through conditions 2a and 2b, wireless nodes can not increase their allocation values by switching their uplink connection.

Wireless nodes will keep improving their allocation values until a stable network is reached. However, if the stability model of Definition 6 is assumed, the resulting network may not be an efficient one (see Definition 3) because only pairs of directly connected players are being checked for better allocation values at conditions 2a and 2b of Definition 6. Some allocation value improvements may only be achieved by establishing and/or severing two or more
wireless connections simultaneously, which by themselves alone do not bring any benefit. Stronger stability models exist in the literature. For instance, in [23], a stronger stability is presented where all combinations of connections and players are checked for possible allocation value improvements, instead of considering pairs of directly connected players only. However, such strong stability is computationally expensive. Note that the objective in this article is to develop an energy efficient routing algorithm and its computation also consumes energy. A computationally expensive routing algorithm could deter any efficiency gained through careful route choices [12]. In this article, a stable and not efficient network, is termed hidden profitable network.

Definition 7 (Hidden Profitable Network). A network \( g \in G \) is a hidden profitable network if it is complete connection stable, according to Definition 6, and is not efficient, according to Definition 3.

3.2. Network Formation Processes

Complete connection stability merely indicates the desired network configuration properties. A process is still needed to actually achieve a complete connection stable and, if possible, efficient network. That is, connections will have to be established or severed to create routes that are as energy efficient as possible. Here, the focus will be on dynamic approaches where networks are formed over several iterations, instead of using one-time non-cooperative game models, which do not consider that the order in which connections are established or severed can lead to different results [8, 24].

Before introducing the dynamic formation processes considered in this article, it is important to mention that these processes assume a knowledge of the duration of transmission, reception and sleep periods. In the case of collision avoidance MAC protocols, such periods would have to be estimated according to the sleeping procedures in use, while with bandwidth allocation MACs such information is readily available.

The dynamic network formation processes under analysis are discussed next.

3.2.1. Dynamic Network Formation (DNF)

This approach, introduced in [24], starts from an empty network, with no established connections, and then establishes or severs connections, at each iteration, in order to increase the allocation values of the players involved in the connection establishment/dissolution. The process ends when a stable network is reached.

The DNF has one drawback. There is no guarantee that every MAP will have one established uplink connection, i.e. a wireless connection that leads to an MPP and through which traffic can be sent/received to/from the Internet. Moreover, it is even possible to get stuck at an empty network, i.e. a network without any established connection [8]. Such scenarios contradict the first condition of the complete connection stability from Definition 6, which dictates that every MAP \( i \in \mathcal{R} \) needs to have one established connection that leads to an MPP. That is, a complete connected stable network may not be reached. Hence, a modified version of DNF, introduced in [9] is used. This modified DNF starts from a network \( g \) where every MAP has already one established uplink connection. From this starting point, and at each iteration, one established uplink connection may be replaced by another one that is not in use, ensuring that every MAP has one established uplink connection. Its operation can be described as follows:

Step 1: Randomly choose a MAP \( i \in \mathcal{R} \).

Step 2: Determine if \( i \) can have its allocation value increased by replacing its current uplink connection, \( ij \in g \), by another one that is not in use, \( ik \notin g \). Note that the MAP \( k \), at the other end of the new uplink connection, will only accept this new connection if it does not decrease its own allocation value. If there is more than one wireless connection that satisfies this condition, then the one that provides the highest allocation value increase to \( i \) is used. In case the uplink connection of \( i \) is changed, allocation values of wireless nodes affected by this change will have to be recalculated.

Step 3: If the current network, \( g \in G \), is complete connection stable, then the process ends. Otherwise, go back to Step 1.

From here on, the modified DNF will simply be called DNF.

A drawback of DNF, however, is that it may get stuck in a hidden profitable network. Two approaches that are able to overcome this issue are: i) stochastic network formation (SNF), which introduces some randomness when deciding if a connection should be established/severed; ii) farsighted network formation (FNF), which determines or predicts connection changes that are not immediately profitable but may lead to future higher improvements [8].
3.2.2. Stochastic Network Formation (SNF)

This approach randomizes decisions in order to disrupt hidden profitable networks and unlock further improvements. Several versions of this approach exist in the literature [8]. These, however, allow the existence of unconnected players, a scenario that is not acceptable in FiWi access networks. For that reason, in this article, a modified version of SNF, based on the already presented DNF, is proposed. This is composed of two stages. First, DNF is run until a complete connected stable network is reached. At this point, a hidden profitable network is reached, which means that the allocation values can not be increased by switching single uplink connections. Then an iterative second stage starts where, similarly to DNF, a MAP is randomly chosen at each iteration. If the chosen MAP has a link that provides a greater bandwidth allocation, then that link is chosen to become the next uplink connection with probability \( p \). If more than one connection can improve the bandwidth allocation, then the first to be found, and chosen with probability \( p \), will be the one used. Note that only connections improving bandwidth allocation are considered. This avoids pure random choices that could result in meaningless connection changes. When a change is made at the second stage, then the first stage will be run again. The SNF ends when no changes occur at the second stage or after the first stage has run for a maximum number of times. SNF can be described as follows:

**Step 1:** Run DNF.

**Step 2:** Start second stage:

**Step 2.1:** Randomly choose a MAP \( i \in R \).

**Step 2.2:** Search for wireless connections of \( i \) that are not being used and can increase the bandwidth allocation of \( i \) if used as its new uplink. The first of such connections to be found, and selected with probability \( p \), will become the new uplink of \( i \). In case the uplink connection of \( i \) is changed, allocation values of wireless nodes affected by this change will have to be recalculated.

**Step 2.3:** If DNF ran already for the maximum number of times, then end the simulation. Otherwise, go back to Step 1.

3.2.3. Farsighted Network Formation (FNF)

This approach tries to predict connection changes that are not profitable but will allow higher improvements in the future. Similarly to SNF, the approaches in the literature allow the existence of unconnected nodes, which is not desirable in our case because some wireless nodes would not be able to forward traffic from connected clients [8]. Here, a version of FNF tailored to our needs is presented. At a first stage, DNF is run until a complete connection stable network is reached. Then a second iterative stage starts where a group of MAPs are randomly chosen at each iteration. If that group of MAPs can increase their allocation values by simultaneously changing their uplink connections, then the uplink connections will be changed accordingly. Note that these uplink changes would not be profitable if done individually. Only a limited number of simultaneous uplink changes can be tested, otherwise the processing time would be very long. The objective of this second stage is to get out of the hidden profitable networks, where DNF gets stuck, improving allocation and network values. When a change is made at the second stage, the first stage will then be run again. If no changes occur at the second stage, then FNF ends execution. FNF can be described as follows:

**Step 1:** Run DNF.

**Step 2:** Start second stage:

**Step 2.1:** Randomly choose a group of MAPs, either belonging to the same component or different components. The number of MAPs to choose is equal to the number of allowed simultaneous uplink changes.

**Step 2.2:** Calculate the allocation values for all combinations of uplink changes involving the chosen MAPs.

**Step 2.3:** If there are combinations of uplink changes that lead to allocation value increases, then choose the combination that provides the highest aggregate increase to all MAPs and go back to Step 1. Otherwise, proceed to the next step. In case of uplink connection changes, allocation values of wireless nodes affected by these changes will have to be recalculated.
Step 2.4: If all combinations of MAPs were already chosen in Step 2.1 without any uplink connection change, then the process will end. Otherwise, go back to Step 2.1 to choose another group of MAPs.

4. Energy Efficient Routing using a Network Game Model

4.1. Energy Consumption

Energy efficient routing methods in FiWi access networks should be aware of the capabilities of optical and wireless technologies in an integrated manner. That is, routes at the wireless front end should be established by taking into consideration the energy consumption of optical and wireless transceivers, as well as the scheduling policy for sleeping periods. Furthermore, when accounting for the total energy expenditure, one has to consider that traffic from/to a source/sink will be forwarded through several hops, affecting wake and sleeping periods of several nodes. Hence, in this article, each wireless node \( i \in \mathcal{W} \) will be held accountable for part of the energy consumed at nodes in \( \Gamma_i \). More specifically, \( i \in \mathcal{W} \) will be accountable for: (i) the energy that nodes in \( \Gamma_i \) consume to transmit/receive traffic belonging to \( i \); (ii) part of the energy that nodes in \( \Gamma_i \) consume while in sleep mode; (iii) part of the unproductive energy that nodes in \( \Gamma_i \) consume. These three constituents of the energy consumption will be denoted by \( e_{DLV}^i \), \( e_{SLP}^i \) and \( e_{UNP}^i \), respectively. It will be assumed that nodes will always go to sleep whenever there are no scheduled transmissions or receptions of local or foreign traffic. The only exception is when the time until the next scheduled transmission or reception is shorter than the time needed to switch to sleep mode and wake up again. This time, during which a node is in wake mode without transmitting or receiving traffic, is called unproductive time and the energy consumed during this period is termed unproductive energy. The total energy consumed by all transceivers, in order to send and receive traffic emanating/arriving from/to a node \( i \in \mathcal{W} \), can be calculated by:

\[
e_i = e_{DLV}^i + e_{SLP}^i + e_{UNP}^i.
\]

When determining \( e_{DLV}^i \), \( e_{SLP}^i \) and \( e_{UNP}^i \), the term byte time will be used to refer to the time that one byte takes to be transmitted or received by a device, which can be a wireless radio or an optical transceiver. The following notation is assumed for values that do not change during network lifetime:

- \( E^O \) Energy per byte time that is consumed by the transceiver of an ONU in wake mode.
- \( E^T \) Energy per byte time that is consumed by a wireless radio in transmit mode.
- \( E^R \) Energy per byte time that is consumed by a wireless radio in receive mode.
- \( E^S_i \) Energy per byte time that is consumed by the transceiver of node \( i \in \mathcal{N} \) in sleep mode.
- \( E^W_i \) Energy per byte time that is consumed by the transceiver of node \( i \in \mathcal{N} \) when waking up.
- \( \text{cap}_i \) Byte rate capacity of the radio transceiver of wireless node \( i \in \mathcal{W} \).
- \( t^S_i \) Number of byte times that a node \( i \in \mathcal{N} \) spends in sleep mode.
- \( t^W_i \) Number of byte times that a node \( i \in \mathcal{N} \) takes to wake up.
- \( t^UR_i \) Number of byte times that the radio of a wireless node \( i \in \mathcal{W} \) spends in receive mode without actually receiving traffic. That is, unproductive time while in receive mode.
- \( t^UT_i \) Number of byte times that the radio of a wireless node \( i \in \mathcal{W} \) spends in transmit mode without actually transmitting traffic. That is, unproductive time while in transmit mode.
- \( t^UW_i \) Number of byte times that the optical transceiver of an ONU \( i \in \mathcal{O} \) spends in wake mode without actually transmitting or receiving any traffic. That is, unproductive time in wake mode.

Besides the just mentioned notation, additional variable become necessary, which may change according to network conditions such as the currently established routes:
$B_i$ Local traffic load of wireless node $i \in \mathcal{W}$. This load is defined as a portion of $\text{cap}_i$.

$B_i^T$ Bandwidth allocation at $i \in \mathcal{W}$ for downstream and upstream local traffic. This is a portion of $\text{cap}_i$ that is allocated to $i$. It is assumed that TDM is used by transmissions within the interference range, hence, $B_i^T$ will be adjusted according to the load and bandwidth allocation of interfering nodes, so that the medium is shared and interferences are avoided.

$h_i$ Number of hops between MAP $i \in \mathcal{R}$ and its MPP along the corresponding component.

### 4.1.1 Energy consumed when delivering traffic

As aforementioned, packets will have to go through several hops in order to reach a specific ONU or MAP, considering upstream and downstream transmissions respectively. This means that the delivery of $B_i^T \text{cap}_i$ bytes, emanating/arriving from/to MAP $i$, will consume $B_i^T \text{cap}_i \left( h_i \left( E^T + E^R \right) \right)$ Joules at the front end, assuming that wireless radio transceivers consume $E^T$ Joules per byte time in transmit mode, $E^R$ Joules per byte time in receive mode and that $i$ is $h_i$ hops away from its MPP. As for the back end, it is considered that the transceiver of an ONU consumes $E^O$ Joules per byte time when in wake mode to send/receive packets. Therefore, the total energy consumed to deliver $B_i^T \text{cap}_i$ bytes to/from node $i$ is:

$$e_{i}^{DLV} = B_i^T \text{cap}_i \left( E^O + h_i \left( E^T + E^R \right) \right).$$

(2)

For simplicity, the energy consumed to transfer packets between MPPs and ONUs is not taken into consideration, as MPPs can be connected or attached to ONUs in many different ways and can support many different working modes [3, 25].

### 4.1.2 Energy consumed when in sleep mode

Assuming that the transceiver of a node $i \in \mathcal{N}$ consumes $E^S_i$ Joules per byte time in sleep mode and stays in that mode for $t^S_i$ byte times, then $i$ will consume $t^S_i E^S_i$ Joules while in sleep mode. The time that $i$ takes to wake up from sleep/standby needs also to be considered. If node $i \in \mathcal{N}$ takes $t^W_i$ byte times to wake up and uses $E^W_i$ Joules per byte time, then it will consume a total of $t^S_i E^S_i + t^W_i E^W_i$ Joules during sleep mode and while waking up.

The time that a node $i \in \mathcal{N}$ stays in sleep mode depends on local traffic and on traffic to/from nodes in $\Gamma^-_i$. Therefore, the energy spent in sleep mode should be divided among all nodes in $\Gamma^+_i \cup \{i\}$. Similarly, $i$ also influences the sleeping periods of nodes in $\Gamma^-_i$ and, as such, should be held accountable for a portion of the energy that those nodes consume while in sleep mode and waking up. Hence, node $i \in \mathcal{W}$ is responsible for the consumption of the following amount of sleep mode energy:

$$e_{i}^{SLP} = \left[ \sum_{j \in ((\Gamma^+_i \cup \{i\}) \cap \mathcal{W})} \frac{t^S_i E^S_j + t^W_i E^W_j}{|\Gamma^+_i \cup \{j\}|} \right]$$

$$+ \frac{t^S_i E^S_i}{|\Gamma^-_i \cap O|} + \frac{t^W_i E^W_i}{|\Gamma^+_i \cap O|},$$

(3)

where the first part accounts for the consumption at wireless nodes in $\left( (\Gamma^-_i \cup \{i\}) \cap \mathcal{W} \right)$, that will be required to forward traffic belonging to $i$, and the second part accounts for the consumption at the ONU being used by $i$, $\Gamma^-_i \cap O$.

### 4.1.3 Unproductive energy consumed in wake mode

Assuming that the radio of a wireless node $i \in \mathcal{W}$ spends $t^U^T_i$ and $t^U^R_i$ byte times in transmit and receive mode, respectively, without sending or receiving traffic, then the unproductive energy consumed at $i$ will be: $t^U^T_i E^R + t^U^T_i E^T$. Similarly to wireless nodes, ONUs may also have unproductive time periods. Considering that the transceiver of the ONU, used by a wireless node $i \in \mathcal{W}$, stays in wake mode for $t^W_{\Gamma^+_i \cap O}$ byte times without sending or receiving traffic, then the ONU will consume $t^U_{\Gamma^+_i \cap O} E^O$ Joules of unproductive energy. Similarly to what was done in expression (3), the unproductive energy consumed at node $i \in \mathcal{N}$ should be divided among all nodes in $\Gamma^+_i \cup \{i\}$, and a portion of
the unproductive energy of nodes in $\Gamma_i$ should be assigned to $i$. Hence, every node $i \in W$ is responsible for the consumption of the following amount of unproductive energy:

$$e_i^{\text{UNP}} = \sum_{j \in (\Gamma_i \cup \{i\}) \cap W} \left( \sum_{k \in W} \frac{e_j^{\text{UE}} + e_j^{\text{UT}}}{|\Gamma_j \cup \{j\}|} \right) + \frac{e_i^{\text{UE}}}{|\Gamma_i \cup O|},$$

where the first part accounts for the consumption at wireless nodes in $\left( \Gamma_i \cup \{i\} \right) \cap W$, that will be required to forward traffic belonging to $i$, and the second part accounts for the consumption at the ONU being used by $i$, $\Gamma_i \cap O$.

### 4.2. Network Game Model

Since our goal is to find the most energy efficient routes, expressions (2), (3) and (4) will become part of the value function, $\Upsilon(g)$, so that a network value is obtained (see Definition 2 in Section 3.1). One might think that the overall energy efficiency, $\sum_{i \in W} \frac{E_i^{\text{cap}}}{E_i^{\text{cap}}}$, should be used to calculate the network value. However, the use of such function may lead to paths that, although energy efficient, would forward just a small fraction of the intended traffic. To avoid this, the fraction of traffic successfully delivered, $\frac{\sum_{i \in W} B_i^t \text{cap}_i}{\sum_{i \in W} \text{cap}_i}$, should also be taken in consideration. Hence, in this article, the network value of a network $g \in G$ is calculated using:

$$\Upsilon(g) = \frac{\sum_{i \in W} B_i^t \text{cap}_i}{\sum_{i \in W} \text{cap}_i} \sum_{i \in W} B_i^t \text{cap}_i.$$  

The second part of expression (5) has a cutback effect on the energy efficiency calculation. That is, if a certain path layout is only able to forward half of the traffic, then its efficiency will be halved.

As for the allocation rule used to distribute the network value among all wireless nodes, an *egalitarian allocation rule* is used:

$$\nu_i(g) = \frac{\Upsilon(g)}{|W|}.$$  

This allocation rule distributes the network value equally among all players, aligning the network value with the individual interests of players and avoiding cycles [8]. More specifically, a cycle is a sequence of improving networks $\{g_1, g_2, \ldots, g_K\}$ where $g_1 = g_K$ and $\forall k = \{1, 2, \ldots, K - 1\}, \exists i : \nu_i(g_k) < \nu_i(g_{k+1})$. In the context of FiWi access networks, the existence of such cycle would mean that MAPs would always be changing their uplink connections without ever stabilize. As such, this egalitarian allocation rule ensures a convergence to a stable network when used with any of the presented formation processes.

Note that in FiWi access networks the wireless nodes receive electricity from the grid and not from batteries. Thus, when $\nu_i(g)$ is divided among all wireless nodes, the overall energy consumption is being optimized.

### 5. Comparison of Network Formation Processes

#### 5.1. Simulation Setup

In order to identify the formation process that gives rise to the most energy efficient network, and to understand how each process changes the network in order to increase energy efficiency, which will be useful to develop an efficient heuristic algorithm, a set of simulations were done. For this purpose, several random networks, composed of MAPs, MPPs and ONUs, were generated using the weighted proximity algorithm [26]. The parameters used to build these networks are summarized in Table 1. Different combinations of network size, number of MPPs and load range were tested. Ten different networks of each size were created and, for each network, five different MPP placements were done, for $|g| = 3, 4$ and 5. An uniform distribution was used to select MPPs among network nodes. For each combination of network size, MPP placement and load, five simulations were done using different seeds for random number generation. ONUs were placed near MPPs and connected using Ethernet links.

In what concerns to network formation processes, as explained in Section 3.2, a starting point is needed where every MAP has already one established uplink connection that leads to an MPP. In these simulations, the shortest path (SP) was used as the input for all formation processes since it is a widely used routing method and may serve as a
Table 1: Parameters given to the network generator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wireless nodes,</td>
<td>15; 19; 23; 27</td>
</tr>
<tr>
<td>Number of MPPs,</td>
<td>3; 4; 5</td>
</tr>
<tr>
<td>Load ranges of wireless nodes</td>
<td>0-0.5; 0.2-0.7; 0-1; 0.5-1</td>
</tr>
<tr>
<td>Average node degree</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 2: Energy consumption during one byte time, calculated with the power consumptions obtained from [5, 27].

<table>
<thead>
<tr>
<th>Energy Consumption</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transceiver of ONU in wake mode</td>
<td>$E^0_i = 30.8 \times 10^{-9}$J</td>
</tr>
<tr>
<td>Transceiver of ONU in sleep mode</td>
<td>$E^s_i, i \in O = 6 \times 10^{-9}$J</td>
</tr>
<tr>
<td>Radio of a wireless node in transmit mode</td>
<td>$E^T_i = 140 \times 10^{-9}$J</td>
</tr>
<tr>
<td>Radio of a wireless node in receive mode</td>
<td>$E^R_i = 60 \times 10^{-9}$J</td>
</tr>
<tr>
<td>Radio of a wireless node in standby</td>
<td>$E^W_i, i \in W = 0.8 \times 10^{-9}$J</td>
</tr>
<tr>
<td>Radio of a wireless node when waking up</td>
<td>$E^W_i, i \in W = 140 \times 10^{-9}$J</td>
</tr>
</tbody>
</table>

As for SNF, different experiments were done for different values of $\epsilon$ (from 0.1 to 0.5, in steps of 0.1) and it was set to run the first stage up to five iterations.

The considered energy consumptions per byte time are shown in Table 2. Such values were obtained considering that ONUs have a bandwidth capacity of 1Gbps for upstream and 1Gbps for downstream, consume 3.85W in wake mode, 0.75W in sleep mode and take 3.5ms to wake up [5, 27]. Radios have a bandwidth capacity of 100Mbps, which has to be shared among downstream and upstream, consume 1.75W in transmit mode, 0.75W in receive mode, 0.01W in standby and take 5ms to wake up [12]. Therefore, the number of byte times that the transceiver of an ONU and radio of a wireless node take to wake up will be $t^W_i = 437500, \forall j \in O$, and $t^W_i = 62500, \forall j \in W$, respectively.

As for bandwidth allocation, each wireless node $i \in W$ will have an allocated bandwidth, $B_i^T$, proportional to its load, $B_i$. For instance, if a node $i$ has twice the load of a node $j$, $B_i = 2B_j$, then $i$ will have twice the allocated bandwidth of $j$, $B_i^T = 2B_j^T$.

5.2. Analysis of Results

In this section, the average network value, average energy efficiency and average bandwidth allocation of the results obtained by formation processes, when applied to all the tested network scenarios, will be analyzed. Conclusions will allow us to obtain insights on how energy efficient routes can be created and where in the network it is more likely that route changes will produce energy efficiency improvements. This will serve as a basis for the development of a heuristic algorithm.

The average network values, $\bar{T}(g)$, obtained by the formation processes, are plotted in Fig. 3(a). As can be seen, all formation processes were able to obtain higher network values than SP. FNF provides the highest average network value, approximately $0.02 \times 10^6$ more than DNF. This means that FNF was able to overcome hidden profitable networks where DNF was stuck and, as a result, network values were improved. As for SNF, an average network value better than SP is obtained, although much smaller than the one obtained by DNF. Such result means that the random method of SNF, to surpass hidden profitable networks, is not good enough and ends up making uplink changes that do not produce network value improvements. In fact, as shown in Fig. 4, with higher values of $\epsilon$ (see Section 3.2.2), the results of SNF get worse in terms of average network value, $\bar{T}(g)$, average energy efficiency, $\frac{\sum_{i \in W} B_i^T \cdot \text{cap}}{\sum_{i \in W} B_i}$, and average bandwidth allocation, $\frac{\sum_{i \in W} B_i^T \cdot \text{cap}}{\sum_{i \in W} B_i}$. 


Table 3: Average number of hops of the paths obtained by the several formation processes and SP.

<table>
<thead>
<tr>
<th></th>
<th>Average number of hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>1.495</td>
</tr>
<tr>
<td>DNF</td>
<td>1.585</td>
</tr>
<tr>
<td>SNF</td>
<td>1.914</td>
</tr>
<tr>
<td>FNF</td>
<td>1.604</td>
</tr>
</tbody>
</table>

Figure 3: Average results of the tested formation processes and SP: (a) network value; (b) energy efficiency; (c) allocation ratio.

Let us now look into the energy efficiency and bandwidth allocation ratio, shown in Fig. 3(b) and Fig. 3(c). From these plots, it is possible to state that the good network values obtained by FNF are a reflex of an increase in both energy efficiency and bandwidth allocation ratio. More specifically, the energy efficiency of FNF is $0.02 \times 10^6$ higher than the one obtained by DNF. This means that FNF, in average, is able to send 20kB more than DNF for each Joule, while slightly increasing the average bandwidth allocation ratio. When compared to SP, FNF is able to send 80kB more for each Joule, while having an average bandwidth allocation ratio of almost 60% against 53% of SP.

The higher energy efficiency and higher bandwidth allocation results obtained by DNF and FNF, when compared to SP, are due to a good selection of paths. More energy efficiency paths, avoiding congested areas of the network, are chosen. Concerning the number of hops, one might think that DNF and FNF paths may become too long, when compared with SP, increasing delays. However, as shown in Table 3, the average number of hops, of the paths obtained by the formation processes, increased only marginally when compared to SP. In fact, if the number of hops increased too much, then the energy efficiency could actually decrease, since traffic would have to be forwarded through too many hops and more energy would be consumed to deliver the same amount of traffic. This means that the average delays associated with the formation processes and SP are expected to remain similar. These observations lead us to the following assumption:

**Claim 1.** Surpassing hidden profitable networks in an accurate way, which is the case of FNF, leads to significant increases in both energy efficiency and successful traffic delivery, while maintaining similar delays.

In average, FNF obtains the best results. However, it is necessary to check whether or not that observation still holds for different network conditions. In Fig. 5, the results obtained by DNF, SNF and FNF are compared with the results of SP, as the ratio of MAPs per MPP increases. Note that these are average results considering all tested network traffic loads. In terms of network value, Fig. 5(a), FNF always obtains the best results for any ratio of MAPs per MPP. As for bandwidth allocation, Fig. 5(c), FNF also obtains the best results for any number of MAPs per MPP, even if just by a small margin. Regarding energy efficiency, Fig. 5(b), both DNF and FNF have negative percentages when $\frac{R}{G} < 3$, meaning that they were not able to get better results than SP. This is so because, in networks with a small number of MAPs per MPP, there are not enough alternative paths that can be exploited to improve energy efficiency and the only way to improve network value is to balance traffic throughout the network, improving traffic successfully delivered. When $3 \leq \frac{R}{G} \leq 4$, DNF and FNF are similar to SP, i.e. there is no increase over SP. From there on, i.e. for
\(|R|/|G| > 4\), DNF and FNF always obtained better results than SP, while FNF obtains better results than DNF. Hence, we may conclude the following:

**Claim 2.** FNF, in terms of network value and successful traffic delivery, always performs better than SP, DNF and SNF for any number of MAPs per MPP. As for energy efficiency, FNF is also able to perform better, except when the network has a very low ratio of MAPs per MPP.

Another network condition that may affect the results is the network traffic load. In Fig. 6, the results obtained by DNF, SNF and FNF can be compared with the results of SP for different network traffic loads. Note that these are average results considering all possible ratios of MAPs per MPP. In what concerns to network value, Fig. 6(a), and traffic successfully delivered, Fig. 6(c), FNF always obtains better results when compared to the other methods. In terms of energy efficiency, Fig. 6(b), when average traffic is low, 0.25, DNF and FNF obtained lower results than SP. This means that when traffic load is low, it is difficult to establish routes that can efficiently optimize the scheduled transmission, reception and sleep periods. However, for higher traffic loads, FNF obtains better results than any of the other methods. Therefore, we can assume the following:

**Claim 3.** FNF, when compared to SP, DNF and SNF, obtains better results in terms of network value and successful traffic delivery for any network traffic load. As for energy efficiency, the results of FNF are similar to the ones of SP and DNF when network traffic load is low, however, when network traffic load is high, FNF achieves a better energy efficiency.

### 5.3. Computational Time

In general, FNF obtains the best results in terms of network value, energy efficiency and bandwidth allocation ratio. However, it is also the most computationally expensive, even if only three MAPs are checked for a simultaneous
Figure 6: Effect that the tested loads have on: (a) network value; (b) energy efficiency; (c) bandwidth allocation ratio.

6. Network Formation Heuristic Algorithm

According to Claims 1, 2 and 3, the FNF, when compared to the other formation processes, obtains the best results except for a small number of situations.

To tackle the high computational time that FNF requires, a heuristic algorithm can be developed that detects and improves hidden profitable networks only at components with the highest average node degree or highest average traffic load, according to Claim 4. This way, only nodes that belong to such components need to consume energy detecting and solving hidden profitable networks.

6.1. Heuristic Algorithm

For the operation of the heuristic algorithm, every node will have to acknowledge information to all the other nodes. This includes traffic load, currently allocated bandwidth and established route to the MPP. Such information

2Here, \( \binom{c}{R} \) refers to the number of combinations of \( c \) nodes from set \( R \)
can be exchanged through link state advertisements (LSAs), similarly to other link state algorithms. The time between LSAs exchange can be defined according to the network conditions. That is, a bursty network will need more LSA exchanges, for more frequent network information update, while a less bursty network can work properly with less LSA exchanges. Another possibility is to exchange LSAs whenever changes occur (e.g. traffic load, bandwidth allocation, routes).³

This algorithm is assumed to start from a network with the connections of shortest paths established. Every MAP executes the heuristic algorithm, which is composed of two stages:

6.1.1. First stage

The MAP checks if it can improve its allocation value by switching the current uplink to another one. Among all possible uplink changes, the one that brings the highest improvement is adopted.

At this first stage, a MAP $i \in R$, searching for the uplink connection that brings the best network value, does not need to worry about the effect that its uplink change will have on every wireless node of the FiWi access network. This is so because, only wireless nodes that belong to the same dependency set will be affected by the uplink change of $i$. To understand the notion of dependency set, let us consider Fig. 8 that illustrates the switching possibilities for MAP 1. When this MAP is checking if link A brings a better network value, then the dependency set includes all MAPs in component $C_1$. When link B is being tested, the dependency set includes the wireless nodes from components $C_1$ and $C_2$. When link C is tested, the dependency set includes the wireless nodes from components $C_1$ and $C_3$. In summary, the components including the end nodes of links involved in the switching operation will be the ones that will make up the dependency set.

If a MAP can not find a better uplink, and if it belongs to a component with the highest average node degree or highest average traffic load, then the algorithm will pass on to the second stage.

6.1.2. Second stage

The MAP will try to discover better outcomes that can only be reached if its uplink connection is switched together with the uplink of other MAPs, i.e. the MAP will try to detect and solve hidden profitable networks. Similarly to FNF, the proposed heuristic algorithm considers a limited number of simultaneous uplink changes. If a better outcome is found, then the MAP switches its uplink to the new one and informs, through special LSAs, all the affected MAPs so that their uplinks are also changed.

³Note that the heuristic algorithm could also run centrally. In that case, every node would have to exchange control messages with the central node for routes to be computed and established.
At this stage, a MAP $i \in R$ does not need to check all MAPs of the FiWi access network for simultaneous uplink connection changes. Only the MAPs that can affect $i$ need to be considered. To understand which MAPs are these, let us introduce the term \textit{dependency super-set}. The dependency super-set of a MAP $i \in R$ is denoted by $S_i$ and is the union of all dependency sets that result from all possible uplink changes of $i$. In the example of Fig. 8, the dependency super-set of MAP 1 includes all nodes from components $C_1$, $C_2$ and $C_3$. The nodes that need to be considered for simultaneous uplink change with $i$ are the ones whose dependency super-sets intersect. For instance, if up to three simultaneous uplink changes are allowed, $c = 3$, then only the MAPs $j \in R$ and $k \in R$ that obey to the following condition will be considered for simultaneous uplink connection change with $i$: $S_i \cap S_j \cap S_k \neq \emptyset$.

The computational time of the heuristic algorithm depends on the number of nodes having dependency super-sets intersection. Since the intersection of dependency super-sets is composed of entire components, the computational time depends on the number of possible link changes involving the wireless nodes belonging to those components. That is, on average, $\binom{n}{2}d^c$ link changes have to be considered, where $c$ is the maximum number of simultaneous uplink changes, $\frac{\left| R \right|}{\left| G \right|}$ is the expected number of MAPs per component, $n$ is the number of components that will be considered for simultaneous uplink changes and $d$ is the average node degree. As it will be shown in the next section, for small networks with a low number of MAPs and MPPs, FNF and the heuristic algorithm are computationally similar. However, for larger networks, with more MAPs and MPPs, the heuristic algorithm will need less time than FNF. The algorithm is summarized in Fig. 9.

6.2. Simulation and Results

The performance of the heuristic algorithm previously discussed will now be evaluated using the test bed used to evaluate the formation processes in Section 5.

When analyzing the network values, energy efficiencies and bandwidth allocations obtained by the heuristic algorithm (HA), DNF and FNF, shown in Fig. 10, we can state that the performance of HA is between DNF and FNF. The only exception is for the bandwidth allocation ratio, which reflects the traffic successfully delivered. In that case, FNF and HA obtained similar results, with a difference smaller than one percent. This means that, in average, HA is able to surpass hidden profitable networks, improving energy efficiency and bandwidth allocation, when compared to DNF.

The effect that the number of MAPs per MPP has on results is shown in Fig. 11, while the effect of different loads is shown in Fig. 12. Both these results are in accordance to what is observed in Fig. 10. That is, HA provides a network value and energy efficiency (bytes per Joule) that are between DNF and FNF, while providing a successful traffic delivery that is roughly equal to the one obtained by FNF, independently of the ratio $\frac{\left| R \right|}{\left| G \right|}$ or network traffic load. Summarizing, HA solves many of the hidden profitable networks for any network conditions, increasing energy efficiency and delivered traffic, when compared to DNF, and gets close to the FNF results.

The computational time of formation processes, as aforementioned, is also an important issue when energy consumption is a concern. That is because executing the formation processes also consumes energy and, as such, longer execution times will lead to higher energy consumptions. The average processing time of the formation processes, which is the time until no more path changes are made to the network, is shown in Fig. 13 for different network
FirstStage \((i, c, g)\)

/*Inputs:  
\(i\) = node that will have its current uplink connection checked  
\(c\) = maximum simultaneous uplink changes (required for second stage)  
\(g\) = currently established connections*/  
\(l\) = current established uplink connection at \(i\)  
\(l'\) = wireless connection at \(i\) that provides the highest allocation value to \(i\)

if \(l \neq l'\) then  
g = \(g \setminus \{l\} \cup \{l'\}\)
else if \(i\) belongs to a component with the highest average node degree or highest average traffic load then  
g' = SecondStage \((i, c, g)\)  
if \(g \neq g'\) then  
g = g'
end if
end if
return \(g\)

SecondStage \((i, c, g)\)

/*Inputs:  
\(i\) = node that will have its current uplink connection checked  
\(c\) = maximum simultaneous uplink changes  
\(g\) = currently established connections*/  
for all combinations of \(c\) MAPs \((i\) included) whose dependency super-sets intersect do  
\(C\) = set of \(c\) selected MAPs \((i\) included)  
\(l_C\) = set with currently established uplink connections of every MAP in \(C\)  
\(l'_C\) = set of uplink connections involving the MAPs in \(C\), that provides the highest aggregated allocation value  
if \(l_C \neq l'_C\) then  
g = \(g \setminus \{l_C\} \cup \{l'_C\}\)
end if
return \(g\)
end for

Figure 9: Heuristic algorithm to update uplink connection of \(i \in R\).

Figure 10: Comparison between heuristic algorithm, DNF and FNF: (a) network value; (b) energy efficiency; (c) bandwidth allocation ratio.

Sizes. As can be observed, the HA is much faster than FNF, since only nodes that belong to the component with the highest node degree or highest traffic load pass on to the second stage of the algorithm. Also, in accordance with the expected computational time from the previous section, the difference in execution time between HA and FNF tends to increase for larger networks. DNF, in turn, is faster than HA and FNF, since hidden profitable networks are
Figure 11: Effect that the number of MAPs per MPP has on the heuristic algorithm results: (a) network value; (b) energy efficiency; (c) bandwidth allocation ratio.

Figure 12: Effect that the tested loads has on the heuristic algorithm results: (a) network value; (b) energy efficiency; (c) bandwidth allocation ratio.

not detected. The question, however, is whether or not the higher energy efficiency obtained by FNF and HA, when compared to DNF, compensates the longer execution time and, as such, the increase in energy consumption. In cases where infrequent traffic load variations exist and, therefore, infrequent bandwidth allocation variations also exist, the formation processes do not have to be executed very often for routes to be updated. In that case, FNF and HA can be more advantageous than DNF, since the longer execution time can be compensated by the higher energy efficiency obtained.

It is possible to estimate the time interval during which no network condition variations may occur, so that HA and FNF become more advantageous than DNF. To this end, let us introduce the following notation, where \( \text{alg} \) refers to DNF, FNF or HA:

- \( s_{\text{alg}} \): Set of ONUs.
- \( P \): Average power (Watts) used during the execution of the formation process.
- \( \rho_{\text{alg}} \): Joules per byte sent/received, which is a result of the energy efficiency obtained. This is the inverse of the sent/received bytes per Joule introduced in expression (5).
- \( C_{\text{alg}}^i \): Bandwidth allocation of wireless node \( i \in W \) obtained with the routes established by \( \text{alg} \). This bandwidth allocation is equal to \( B^i_{\text{cap}} \), that results from the paths established by \( \text{alg} \).

Using this notation, the energy consumed to execute DNF, FNF and HA can be calculated by \( P_{S_{\text{DNF}}} \), \( P_{S_{\text{FNF}}} \) and \( P_{S_{\text{HA}}} \), respectively. After all routes have been established, the energy needed to send/receive \( \phi \) bytes with the routes established by DNF, FNF and HA is \( \phi \rho_{\text{DNF}}, \phi \rho_{\text{FNF}} \) and \( \phi \rho_{\text{HA}} \), respectively. Hence, HA will be more advantageous than
DNF if the following condition holds:

\[
P_{S_{DNF}} + \phi p_{DNF} > P_{S_{HA}} + \phi p_{HA} \Leftrightarrow \frac{P_{S_{DNF}} - S_{HA}}{\rho_{HA} - \rho_{DNF}} > \phi.\]  

(7)

This means that if the network conditions stay the same at least for a time interval equal to the time required to send/receive \(\phi\) bytes, then HA will be more advantageous than DNF. The time needed to send \(\phi\) bytes can be calculated by \(\frac{d}{\sum_{i\in W} v_i}\). Naturally, the same reasoning can be applied for FNF, when compared to DNF:

\[
P_{S_{DNF}} - S_{FNF} > \frac{\rho_{FNF} - \rho_{DNF}}{\phi}.\]

The actual time interval, with no changes on network conditions, depends on the power used during the execution, the execution time, the obtained energy efficiency and the bandwidth allocation. The energy efficiency and bandwidth allocation, in turn, as analyzed in Section 5.2 and Section 6.2, depend on the ratio \(\frac{R}{G}\) and on the average traffic load. Hence, ultimately, the time interval with no changes on network conditions is very complex to determine and depends on: the power used, the execution time, the energy efficiency variation according to \(\frac{R}{G}\), the bandwidth allocation variation according to \(\frac{R}{G}\), the energy efficiency variation according to the average traffic load and the bandwidth allocation variation according to the average traffic load. In our test bed, the shortest time that HA needed for the network to stay stable, in order to be more advantageous than DNF, was of 60 seconds, while the longest time was approximately 5 hours. As for FNF, when compared to DNF, the shortest time was of 128 seconds, while the longest was of approximately 11 hours. Hence, the number of scenarios in which the HA will be more advantageous than DNF is higher, when compared with FNF.

7. Conclusions and Future Work

In this paper we address energy efficient routing in FiWi access networks. A network formation game theoretical model for energy efficiency was presented. This model was used to test several network formation processes: DNF, SNF and FNF. From all these formation processes, FNF obtained the highest energy efficiency. However, FNF is computationally the most demanding. To address such demand, an analysis was done to understand where in the network did FNF make the route changes that led to its highest energy efficiency. With this analysis, it was possible to develop a heuristic algorithm that is computationally more efficient than FNF and obtains results close to FNF in terms of energy efficiency.

Future work includes the studying and testing of efficient schemes for LSA exchanges. For instance, MAPs may not need to receive routing, load and bandwidth allocation information from all nodes in the network. A MAP that is
switching its uplink can either remain in the same component or switch to an adjacent one and, therefore, only needs to receive LSAs with information belonging to those components.

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References


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