SAPHYRE

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Abstract

This deliverable describes algorithms and protocols that apply the SAPHYRE resource sharing paradigm in wireless networks. The contribution is twofold: first, to specialize the theoretical findings of SAPHYRE optimizations to practical wireless networks, with several choices for what concerns the technological aspects. Second, we also verify whether he sharing gain envisioned by theory translates to complex scenarios with many nodes and several coexistence issues. The main result of this deliverable is that infrastructure sharing is found to be effective in providing a resource sharing gain, as long as the management is able to coordinate the single entities. In a broad network setup, this can constitute a challenge; however, these results can also push the network operators to further establish this kind of collaborative approach.

Keywords

Resource allocation, protocol design, system level simulation, algorithms.

Contents

Abbreviations

ACK	Acknowledgement
ACK-SCH	Acknowledgement and Scheduling
AI	Allocation Information
AP	Access Point
AR	Allocation Request
AS	Allocation Scheduling
BER	Bit Error Rate
BLER	Block Error Rate
BPSK	Binary Phase-Shift Keying
BS	Base Station
CDMA	Code-Division Multiple Access
CTS	Clear To Send
MAC	Medium Access Control
MUD	Multi-User Detection
PHY	Physical Layer
QoS	Quality of Service
RS	Relay Station
RTS	Request To Send
SC-FDMA	Single Carrier Frequency Domain Multiple Access
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference-and-Noise Ratio
SNR	Signal-to-Noise Ratio
UE	User Equipment
UL	Uplink

1 Executive Summary

This deliverable illustrates an overview of the algorithms developed to exploit resource sharing in wireless networks, as well as of the protocols specifically designed to implement these algorithms [11]. The main aim is to verify how spectrum and infrastructure sharing can be beneficial in terms of capacity and throughput, considering also the overhead required to set up the sharing strategies [3, 15].

When two or more operators deploy networks over the same area, resource sharing can be beneficial for both, if properly exploited. Spectrum and infrastructure sharing are two main aspects which are considered. The former can lead to an efficient utilization of the available bandwidth, with added degrees of freedom, while the latter can improve performance by means of increased spatial diversity [14].

Resource sharing has been proven to be beneficial, at the cost, however, of increased complexity [4]. In fact, when resources are shared, mechanisms must be designed in order to decide which operator is going to use a specific resource element and when. If non orthogonal sharing is applied, interference between the two users must be taken into account; finally, maintaining the fairness between the two resource users can also be a crucial point.

Most of these issues have been analyzed in the SAPHYRE project [5], with attention put on both PHY and MAC layers, and through network simulations. Downlink traffic in cellular networks has been investigated through the use of cross–layers algorithms. The present deliverable aims at analyzing how resource sharing can grant a gain in relay aided networks, where relays can be shared between two co-located wireless networks.

In order to assess the performance improvement that can be achieved, two aspects have been analyzed:

- the design of algorithms which can determine the best performance in a scenario where sharing is enabled. These algorithms are usually based on simplified channel and network models, with the aim of maximizing a given performance metric. In most cases, centralized algorithms are considered, since the highly organized cellular network environment makes it easier to have the algorithm executed by a single entity, which is then in charge of broadcasting the obtained results. Nevertheless, distributed versions of some algorithms can be obtained as well;

- the development of protocols which are able to translate the thoretical gains into practical improvements. In fact, information collection and redistribution, as well as parameters tuning, which are necessary to exploit the shared resources, can be practically obtained by means of control packets exchange. The resulting additional overhead must be considered, in order to assess the effectiveness of resource sharing.

- protocol testing in network simulators is finally necessary to verify how the proposed protocols work. Channel variations, collisions, packet losses can further degrade the performance; properly designed protocols must be able to tackle this issues.

The algorithms and protocols provided by the present deliverable are thought to be applicable to a wide range of wireless networks. More specific implementations, based on the specific peculiarities of existing standards, can be derived. A detailed discussion also including the investigation of PHY and MAC layers is out of the scope of this paper. However, our analysis can be integrated with the existing literature [2, 10, 7] and also fits the other parts explored by the SAPHYRE project [5]. Thus, we believe that the rational behind the proposed solutions can be exploited in several scenarios, integrated with the additional constraints and solutions offered by specific environment features.

The main contributions of the present deliverable are as follows:

- In Section 2.1 we first describe the system model. We put attention to how relays are deployed in the network, and how the random topologies are drawn. In addition, the relay model is defined. The relay capabilities in terms of power, antennas and decoding scheme can strongly influence the network performance, since interference is to be considered, in non orthogonal separation is adopted among concurrent transmissions. In addition, packet superposition and power allocation policies at the relays are also investigated.
- A capacity based performance metric is described in Section 2.2. The metric is analytically derived based on the relay features outlined in Section 2.1, and serve as a basis for a thoretical network capacity calculation. A throughput–based metric is also introduced. Although less general, this metric can take into account the effects of the PHY layer parameters.
- Four different algorithms for UEs allocation are presented in Section 2.3. Designed for a single–network scenario, they can be easily extended to the case of two collaborating networks. These algorithms are centralized, but the first two ones can also be implemented in a distributed fashion. The third and the fourth specifically address the two metrics defined in Section 2.2.
- Section 2.5 shows the theoretical capacity improvements achievable by leveraging spectrum and/or relay sharing. The capacity based algorithm, designed in Section 2.3 is employed, although a very high-level network model is adopted. Non-orthogonal user separation is considered here. Results show that a capacity gain can be achieved in all the considered scenarios, and that spectrum and relay sharing benefits can be superimposed.
- In Section 3.2, we designed two protocols for enabling relay sharing. Since several parameters can be tuned, the two protocols are actually two families of protocols, each of which tries to allocate common resource with different constraints. The first protocol applies the first two algorithms, presented in Section 2.3, in a distributed fashion. Although this may lead to suboptimal

allocation, lower overhead is required. The complete working of the protocols is specified for a given scenario, but can be extended straightforwardly to different scenarios. The second protocol can be used to implement all the algorithms of Section 2.3 in a centralized fashion. The computational burden is committed to the BS, and although more control packets are to be exchanged, the resources can be exploited with more efficiency and flexibility. A third protocol, which makes use of the Opportunistic Routing paradigm, is also designed. The achieved SAPHYRE gain, in terms of throughput, is shown through extensive simulations for all the protocols, in both a CDMA-based and a FDMA-based network scenario.

- For the sake of comparison, in Section 3.3 we extend the previously tested protocols in an ad hoc network scenario. We show that the additional control packets necessary to compensate the lower network organization, as well as the lack of coordination, leads to much lower benefits. Extensive simulations confirms that resource sharing may be beneficial only in some cases.

2 Resource sharing for UL: algorithm design

2.1 Uplink system model

We investigate the performance in a cellular-like network scenario, where two operators decide to share their resources. To evaluate the capacity increase, the main focus is on performance. A single cell is considered as a starting point, where relays are used to support cell edge User Equipment (UE)s. After a brief description of the adopted model, we move to a scenario where two operators have their infrastructures deployed over the same area. If no form of cooperation is employed, each network can be analyzed separately. However, we also assume that the two operators may decide to share their spectrum, their relays, or both. If this is the case, our model lets us clarify which kind of benefits can be achieved, and which are the main challenges in order to fully exploit the additional degrees of freedom.

Firstly, we list the parameters which determine the topology of each network, and therefore of the whole scenario, and which can be tuned in our simulator.

Topology parameters:

- k: number of relays per Base Station (BS);
- N: number of UEs of network;
- d_h: maximum distance of relays from the corresponding BS, and from UEs to at least one relay/BS;

The BSs of the two networks are uniformly deployed in a small square area or side s. For each network, the relays are then deployed. The i–th relay of each network is identified by polar coordinates (r_i, θ_i) in a system referred to the location of the BS. The coordinates are computed as follows:

i) d_i is uniformly chosen in the interval $[\mu d_h, d_h]$, where $\mu \in (0, 1)$;

ii) θ_i is computed as $\theta + 2\pi(i-1)/k + \phi_i$, where θ and ϕ_i are uniform random variables, such that $\theta \sim \mathcal{U}(0, 2\pi)$, whereas $\phi_i \sim \mathcal{U}(-\pi/k, \pi/k)$; all the ϕ_i's are IID.

The UEs are uniformly deployed in a square area which contains all the points within a distance of d_h from at least one relay (or the BS). However, if a UE does not fall within such distance from a relay/BS, it is dropped again.

We call *direct link* the link between a UE and the BS, *access link* the link between a UE and a relay, and *backhaul link* the link between the relay and the BS.

Physical layer parameters

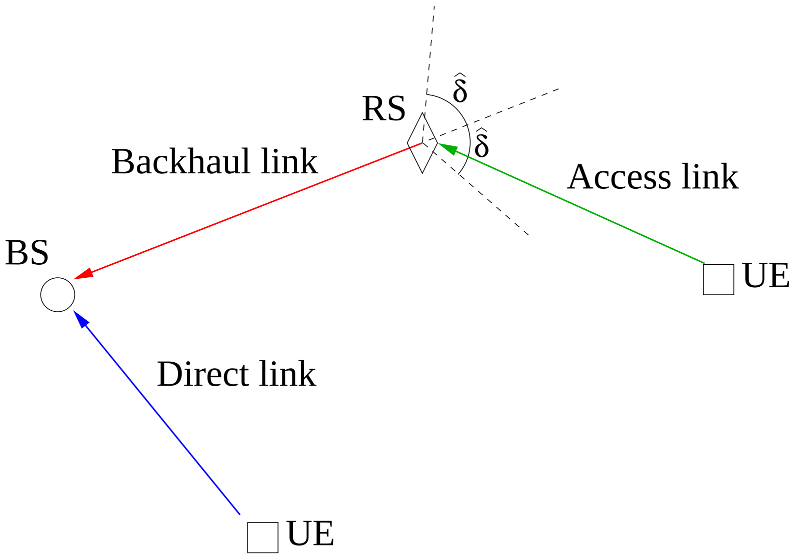

Figure 2.1: Scheme of the links considered in this report. The coverage angle $\hat{\delta}$ of the relay for the access link, is also depicted. Signals coming from UEs in the covered fraction of the plane are not subject to the additional attenuation factor Λ_β.

- P_t: transmission power of the UE;
- P_R: maximum transmission power of the relay;
- N_s: processing gain;
- α: path loss exponent;
- A: fixed path loss component;
- N_0: noise power;
- $\hat{\delta}$: coverage angle at the relays;
- Λ_α: power attenuation factor at BS between backhaul link and direct link;
- Λ_β: power attenuation factor at relays (dependent on antenna pattern);
- Λ_γ: inter-frequency attenuation factor;

The received power P_{rx} over a link of length d, if P_{tx} is the transmission power, is modeled as $P_{rx} = P_{tx} d^{-\alpha}/A$, according to the Hata model[XXX]. The power used by the relay is proportional to the number of the allocated UEs, up to a maximum of P_R. This power is always equally shared among all the allocated UEs. Until the maximum power is reached, a power amount equal to ηP_t is reserved for each UE, with $\eta \in (0, P_R/P_t)$. In other words, if n UEs are allocated to a single relay, the power used by the relay is $\min(n\eta P_t, P_R)$, and this power is equally divided among the n users (it follows that, until $n \leq P_R/(\eta P_t)$, each UE allocated to that relay is granted a power amount equal to ηP_t). An example of the power allocation at the

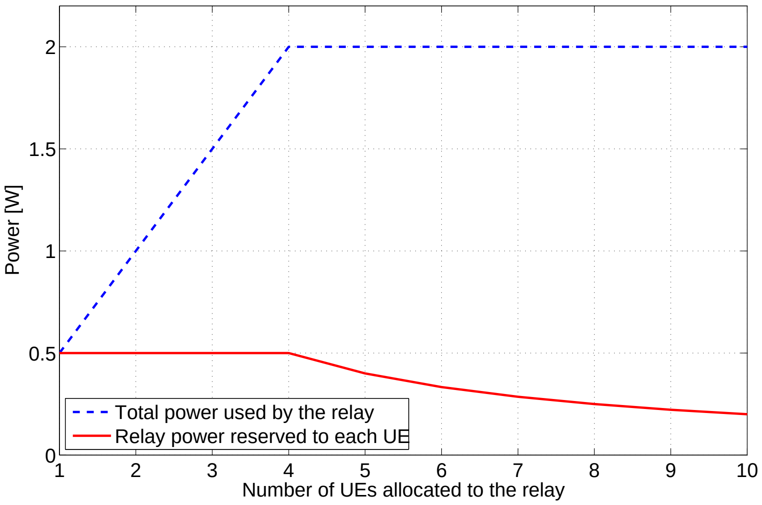

Figure 2.2: Power allocation at the relay, when $P_t = 0.25$ W, $P_R = 2$ W. We assume $\eta = 2$, meaning that an amount of power equal to $2P_t$ is reserved to each relayed UEs, when their number is up to 4. Beyond that value, the relay uses its maximum power transmission, which is equally shared among all the UEs.

relay is depicted in Figure 2.2. Other power allocation choices are possible as well, such as constant transmission power. A more refined allocation scheme may prefer to share the power among the UEs proportionally to the Signal-to-Interference-and-Noise Ratio (SINR) of their access link.

This backhaul link is considered stronger, due to the use of directive antennas at both relays and BSs. This effect is included in the higher power available at the relays, but also leads to neglecting, at the BS, the mutual interference between signals coming from different relays. Moreover, at the same BS, the interference between the signal coming from a BS and the one coming from a UE directly connected to the BS is attenuated by the factor Λ_α.

As regards the access link, we consider a simple antenna pattern, as depicted in Figure 2.1. All the signals coming from directions outside the coverage angle $\hat{\delta}$ (centered on the direction opposite to that of the BS) are attenuated by the factor Λ_β, whereas the ones coming from the directions within the angle $\hat{\delta}$ are not subject to this additional attenuation.

Although other kinds of relaying strategies can be framed as well [6], we limit our analysis to half–duplex relays [12]. It follows that relayed UEs can transmit only for half the time, whereas in the other half the relays transmit (superimposing the signals of the relayed UEs and using the corresponding spreading sequences). We assume that the whole system is synchronized. Therefore, if we consider a slotted time, while the non relayed UEs transmit in all the time slots, the relayed ones transmit only in the odd time slots, while the relays transmit only in the even time slots.

2.2 Metric definition

In order to test the performance improvement which can be granted by spectrum and infrastructure sharing, we define here a capacity-based metric, which can be computed based on the SINRs of the activated links. Although widely used in literature, however, capacity may not be the best choice to analyze the performance of a real network, where several constraints are imposed at all layers. Therefore, we will also briefly introduce a second metric, based on decoding error probability, which can be useful to determine the improvement in terms of throughput achievable via infrastructure sharing.

Both our capacity and error probability computations are based on the SINR perceived by each user. Neglecting the effects of fast fading, we can express the SINRs based on the allocation of the UEs. We start with the case of a single network for the sake of clarity. We call $\mathcal{D}$ the set of the UEs allocated to the BS, whereas $\mathcal{R}_i$ is the set of the UEs allocated to the i–th relay. In addition, we also call d_i the distance between UE i and the BS, r_j the distance between the j–th relay and the BS, and r_{ij} the distance between the i–th UE and relay j. Finally, P_j^R is the power used by relay j, which depends on the number of elements in $\mathcal{R}_j$, as explained above.

For the direct link, the SINR of user i can be expressed as:

$$\Gamma_i^{dir} = \frac{N_s P_t d_i^{-\alpha}/A}{\displaystyle\sum_{p\in\mathcal{D},p\neq i} P_t \frac{d_p^{-\alpha}}{A} + \frac{1}{2}\sum_{j=1}^{k}\sum_{q\in\mathcal{R}_j} P_t \frac{d_q^{-\alpha}}{A} + \frac{\Lambda_\alpha}{2}\sum_{j=1}^{k} P_j^R \frac{r_j^{-\alpha}}{A} + N_0} \tag{2.1}$$

where we fully count the interference from the other non relayed UEs, whereas we time-average the interference coming from relayed UEs. Notice that the processing gain N_s appears at the numerator. In general, it represents the amplification factor applied to the signal of interest in a Multi-User Detection (MUD) decoding scheme. For instance, it may be otained through use of beamforming or of code separation, as in a Code-Division Multiple Access (CDMA) network. We will refer to this second model in the following, but other ones can be considered as well.

For the access link to relay j, the SINR of UE i is instead expressed as:

$$\Gamma_i^{acc} = \frac{N_s P_t \beta_{ij} r_{ij}^{-\alpha}/A}{\displaystyle\sum_{p\neq i} P_t \beta_{pj} \frac{r_{pj}^{-\alpha}}{A} + N_0} \tag{2.2}$$

where now the term β_{ij} is equal to 1 if UE i is deployed in the area covered by relay j (dependent on the coverage angle $\hat{\delta}$), and is equal to Λ_β otherwise. All the UEs, whether relayed or not, interfere on this channel, although the antenna pattern at the relay can substantially lower the interference coming from UEs deployed in the cell center. There is no interference from other relays, which in fact are also receiving the signals from the UEs connected to them.

For the backhaul link between relay j and the BS, the SINR relative to the signal relayed for UE i is:

$$\Gamma_i^{bkh} = \frac{N_s P_j^R / |\mathcal{R}_j| r_j^{-\alpha} / A}{\frac{|\mathcal{R}_j| - 1}{|\mathcal{R}_j|} P_j^R \frac{r_j^{-\alpha}}{A} + \Lambda_\alpha \sum_{p \in \mathcal{D}} P_t \frac{d_p^{-\alpha}}{A} + N_0} \tag{2.3}$$

where we note that the power used by the relay is equally shared among all the $|\mathcal{R}_j|$ UEs allocated to it. In addition, the interference coming from the non relayed UEs is reduced by the factor Λ_α, whereas there is no interference from the relayed UEs (which are silent when the relays are transmitting). Finally, since we neglect the inter-relay interference at the BS, this term is also put to 0.

2.2.1 Capacity-based metric

The capacity of the network is approximated by the sum of the capacities of each UE–BS channel. For the non relayed UE i, its contribution depends only on Γ_i^{dir}). If UE i is instead relayed, then the bottleneck between the access link and the backhaul link has to be considered, and also the halved transmission time has an impact. This results in a capacity given by:

$$C_i = \begin{cases} \log_2(1 + \Gamma_i^{dir}) & \text{if } i \in \mathcal{D} \\ \frac{1}{2} \log_2(1 + \min(\Gamma_i^{acc}, \Gamma_i^{bkh})) & \text{otherwise.} \end{cases} \tag{2.4}$$

The overall network capacity is computed as the sum of the capacities of all the UEs.

When two networks are co-existing, on two different frequencies, then the expressions of the SINRs need to be modified. If no sharing is present, then the interference from the other network has to be simply added at the denominator. This interference is computed exactly as the one of the home network, but reduced by the factor Λ_γ, which accounts for the frequency separation. If $\Lambda_\gamma = 0$, then the two networks do not interfere with each other, and the overall capacity can be computed as the sum of the capacities of the two networks.

If spectrum sharing is enabled, then $\Lambda_\gamma = 1$, since the same frequency is used. This leads to a much higher interference but, on the other side, a double bandwidth is available, and the expression of the capacity in (2.4) requires a multiplication factor equal to 2.

If infrastructure sharing is enabled, then UEs of both networks can be allocated to any relay. In this case, a policy has to be determined about relays transmission. In any case, the power used is proportional to the number of allocated UEs, as described before, but two choices are available:

- single frequency backhaul link: in this case, the relay transmits all the relayed signals on the same frequency (the one of the network it belongs to), and it is up to each BS to be able to recover signals on both frequencies;

- double frequency backhaul link: in this case, the relay divides its power between the two frequencies, by transmitting each relayed signal on the frequency of the network of its original source UE. It follows that it is up to the relays to transmit on two different frequencies.

In both cases each UE transmits on the frequency of its home network (although other choices can be investigated as well), in order to make handover easier. The computation of the SINRs can be performed again with the same equations, keeping in mind that the power used by the relays, in the second case, can be split between the two frequencies. Therefore, if this is the case, the inter–frequency attenuation factor Λ_γ has to be applied only to the fraction of the relay power sent on the other frequency.

If both spectrum and infrastructure sharing are enabled, then the distinction between these two cases does not exist any more, since there is only one frequency band adopted by all users.

2.2.2 Throughput-related metric

We briefly define a second metric, which is based on the decoding error probability, and is hence dependent on the specific Physical Layer (PHY) layer adopted. We call $\varphi(SINR)$ the decoding probability over a given link. Under the assumption of time uncorrelated channels, it follows that the average number or transmission needed for successful packet delivery is $1/\varphi(SINR)$, whose reciprocal can be used as an approximated throughput measure. For the relayed UEs, the minimum between $\varphi(SINR_{acc})$ and $\varphi(SINR_{bkh})$ is to be considered, and divided by a factor 2, due to the half-duplex constraint of the relays. Therefore, the throughput metric for UE i is defined as:

$$T_i = \begin{cases} \varphi(SINR_{dir}) & \text{if } i \in \mathcal{D} \\ \frac{1}{2}\min(\varphi(SINR_{acc}), \varphi(SINR_{bkh})) & \text{otherwise.} \end{cases} \tag{2.5}$$

The overall network throughput value is then obtained by summing the T_i's of all the UEs. Being dependent on the specific parameters and decoding techniques used in the network, we will adopt this metric, and the allocation algorithm based on it, in the protocol simulation section. It must also be noticed that particular signal processing techniques, like beamforming or interference cancellation, may result in complicated or approximated expressions for the error probability as a function of the SINRs. Thus, more than as a real performance evaluation metric, in practical scenarios it can be more useful as a quickly evaluated heuristics.

2.3 Relay allocation

When relays are deployed in a cellular-like network, one of the key issue is to organize how and which transmissions should be helped by them [2]. The number of possible allocations grows exponentially with the number of relays and UEs, making it quite hard to find out the optimal solution with reasonable effort. Therefore,

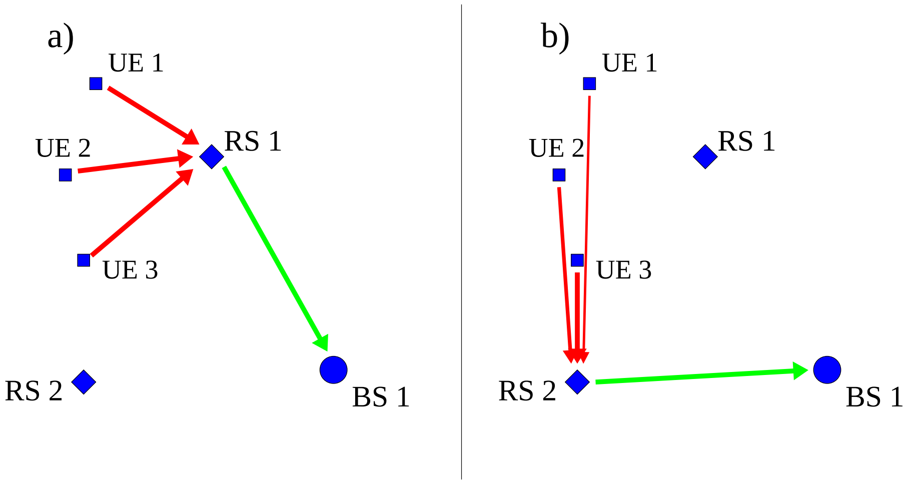

Figure 2.3: Example of two possible allocation. The use of MUD and SIC at the relays may lead to an optimal allocation different from that which minimizes the transmitter–receiver distance.

heuristic approaches are to be designed instead. We propose in the following four possible allocation schemes. The first and the second one are mainly based on the network topology, being shorter links usually more reliable. Although this is true when orthogonal channels are used, in CDMA-like scenarios interference may strongly reduce the effectiveness of this choice. For instance, if we assume that some form of Interference Cancellation is adopted at the relays for decoding, it may be preferable to allocate a user to a farther relays, where, however, signals from interfering users are received with much lower or much higher power, so as to maximize the probability of interference cancellation. Figure 2.3 illustrates an example of a topology which would show this behaviour: in a), three UEs are allocated to the closest relay; however, since their distances from it are similar, also the three received powers are likely to show similar values, making it more difficult to apply interference cancellation. It may be preferable, depending on the channel conditions, the allocation showed in b), where instead the three links are of different lengths, aiding the successive decoding via Successive Interference Cancellation (SIC) [13, 7].

The third approach is founded on the capacity metric defined above. Since it tries to maximize capacity, we will use this one to derive the theoretical capacity gain achievable through resource sharing [8]. Finally, a slight variation of this approach can be used with the aim instead of maximizing the aggregated throughput of the network. We will test this algorithm in the protocol simulation phase, after having set the PHY layer parameters.

2.3.1 Geographic approach (*GEO*)

The first approach to allocate the UEs is to consider their geographic positions [3]. If they are known at the BS, the algorithm simply allocates each UE to the closest relay (or BS). Such an algorithm can also be applied when the geographic knowledge is partial, by choosing the allocation which minimizes the expected distance between transmitter and receiver. An advantage of the *GEO* algorithm is that it can be applied locally in a distributed fashion: unless transmission failures occur, the closest relay can be easily found by the UE via handshaking, as will be shown later. On the other side, however, this kind of allocation may create bottlenecks if the backhaul links are not strong, or if the transmit power of the relays is limited. In fact, in this case, it may happen that a relay is close to a cluster of UEs, and has therefore to forward the traffic of all of them. This may cause long queues at the relay, especially if decoding errors occur between the relay and the BS. A way to avoid this problem is to consider also the load (of buffer occupancy) of the relays.

It must be noticed that the actual distances between nodes should be corrected if attenuation factors are also present. Assuming that the channel between UE i and relay j is affected by the attenuation $\beta_{i,j}$ due to the relay antenna pattern, and by the shadowing coefficient $\omega_{i,j}$, it follows that the average received power at the relay is

$$P = \frac{P_t}{A} \beta_{i,j} \omega_{i,j} d_{i,j}^{-\alpha} \tag{2.6}$$

where $d_{i,j}$ is the actual distance between i and j. However, by measuring the received power, we can define the *effective* distance as $\hat{d}_{i,j} = d_{i,j}/(\beta_{i,j}\omega_{i,j})^{1/\alpha}$.

2.3.2 Geographic–load approach (*GEO-L*)

Differently from the previous allocation algorithm, in this case the UEs are allocated iteratively, after having been sorted based on their distance from the closest available relay (or BS). Effective distances, as computed above, can be used now as well. However, before allocating UE i to relay j, a check is done, to verify that relay j has less than a predefined number N_{MAX} of UEs allocated to it. If this is the case, UE i is instead allocated to the second closest relay, provided that no other UEs are closer to j. If a UE k is closer to j than i, then the algorithm tries to allocate UE k first, and then proceeds with i. If instead no other relays are available, UE i is allocated to the BS. The value N_{MAX} should be set based on the scenario parameters.

The *GEO-L* algorithm ensures that there are no overloaded relays, and then avoids bottlenecks. The main problem is that a change of topology may quickly lead to suboptimal allocations. In fact, if a new UE joins the network, and is located far from the BS but close to a relay j already full, it is forced to transmit directly to the BS, even if one of the UEs already allocated to j could switch to another relay with minor throughput loss.

It follows that this algorithm works best when implemented in a centralized fashion, such that a change of allocations can be easily performed when a topology change requires it.

2.3.3 Heuristic Algorithm for max-capacity (*CBA*)

The capacity of the whole network, as defined in (2.4), depends on how the UEs are allocated to the BS and to the relays. Therefore, a proper allocation algorithm has to be developed in order to maximize the network capacity. As previously observed, the option of selecting a relay for a UE may depend not only on the distance between the UE and the relay, but also on the load of the relay, in terms of relayed UEs. In fact, if the number of UEs allocated to the same relay is too high, the power reserved for each of them in the backhaul link is lower. In addition, it can be observed that, in order to maximize the overall capacity, it is sometimes better to allocate only one UE (say UE i) to a single relay, if their distance is low enough. In fact, adding a farther UE (say UE j) to the same relay, although increasing the capacity for UE j, may highly reduce the one of UE i, leading to an overall lower network capacity.

Clearly, the optimal allocation can be found via an exhaustive search over all the possible allocations. However, the complexity of this search becomes soon unfeasible when the number of relays and UEs grows up. Henceforth, we propose here a Capacity Based heuristic Algorithm (*CBA*) to select an allocation close enough to the optimal one. The rationale behind this iterative algorithm is to add one UE at a time, after having properly sorted them. UEs close to the BS should be immediatley allocated to the BS, since the direct link is much better for them rather than the cell-edge UEs. On the contrary, farther UEs may take advantage from being allocated to a relay, although this is not advantageous for the network, as explained above.

Starting with a single network, we then proceed as follows:

- we first sort the UEs based on their distance from the BS, from the closest to the farthest;
- for each UE i, we compute the capacity obtained by allocating it to the BS and to the various relays;
- if the best selection for UE i is the BS, we confirm this allocation; in fact, all the UEs which are still to be allocated are farther from the BS, and adding one of them to the BS instead of UE i would lead to a lower capacity;
- if instead the best selection for UE i is relay j, we have to check whether there is another UE p which could be allocated to relay j to grant a higher capacity. To do so, we sort the still non allocated UEs based on their modified distance from relay j. The modified distance must take into account also the shadowing attenuation $\omega_{i,j}$ and the antenna pattern, since the UEs not deployed in the area covered by the relay suffer from the additional attenuation factor Λ_β. If r_{ij} is the distance between UE i and relay j, and β_{ij} is the antenna attenuation factor (which is equal to 1 or to Λ_β, depending on the mutual position of i and j), the modified distance is $\hat{r}_{ij} = r_{ij}/(\beta_{ij}\omega_{i,j})^{1/\alpha}$.
- we then check the list of the still non allocated UEs; for each of them, say UE p, we compute the capacity achievable by allocating it to the BS and to every relay; if its best allocation is relay j, and the overall capacity is higher than that achievable by allocating UE i to relay j, then we allocate p to j, and we go back to UE i to verify which is its new best allocation (which may have changed, since now UE p has been allocated). If instead the two conditions are not matched, we proceed with the next UE in the list. If no one of the UEs in the list matches the two conditions, than we can allocate UE i to relay j, and proceed with the next UE.

The algorithm designed can be simplified in some scenarios (for instance, if there is only one network, and the number of relays per BS is 2).

2.3.4 Heuristic Algorithm for max-throughput (*TBA*)

Instead of maximizing the capacity metric, it is possible to maximize the throughput metric, as defined in Section 2.2. Since also this metric is based on the SINR, the corresponding Throughput Based heuristic Algorithm (*TBA*) is very similar to the previous one, with the exception that, when a new allocation is tested, its value is measured in terms of the overall throughput rather than the capacity, computed via (2.5).

2.4 Coexisting networks

Most of the allocation algorithms designed for single networks can be immediately extended to the case of shared relays, both for orthogonal and non-orthogonal sharing [5]. When orthogonal sharing is adopted, the networks simply exchange some of their relays, based on the specific network topology, with the aim of exploiting relays closer to UEs which could otherwise hardly communicate with the BS. In this case, the algorithms described above for maximum capacity or maximum throughput can be implemented separately for each network: for each one, only the relays who are actually being used are taken into account to allocate the UEs.

When non-orthogonal sharing is adopted, the two networks share their relays, which can therefore be used by both of them. As a consequence, the allocation algorithms described above can be implemented taken into account that each UE can be allocated either to its home BS or to any relay, no matter which network it belongs to. The resulting SINRs are computed by considering the relayed signal on the proper frequency (depending on the choice about the backhaul link). For the *CBA* and *TBA* algorithm, the UEs are still sorted based on the distance from their own BS, but if possible they can choose any relay, from both the networks.

The spectrum sharing does not modify the algorithm procedures, but changes the computation of the SINRs, since now all the signals are on the same band, and consequently interfere with each other.

2.5 Capacity theoretical limits

We report the simulation results for the capacity of two co-located networks. One BS per network is considered, with a number of relays k from 2 to 4, and a number of UEs per network from 10 to 20. The capacities are averaged over 1000 simulations per each value, and are depicted in Figures 2.4, 2.5 and 2.6. We do not consider shadowing in this simulation set, which however might increase the gain granted by relay sharing since additional diversity is added. The other parameters are reported in Table 2.1. Additional details on the simulator structure can be found in [9]. It appears that both spectrum sharing and relay sharing are able to increase the

Table 2.1: System Parameters.

Topology	
Relays per network k	2, 3, 4
UEs per network $N_1 = N_2$	10,12,14,16,18,20
Side of BS deploying area s	20 m
Maximum deployment distance d_h	75 m
Relay distance factor μ	2/3
Physical Layer	
UE tx power P_t	0.25 W
Max equivalent relay tx power P_R	2 W
Relay power allocation factor η	2
Processing gain N_s	32
Path loss exponent α	3
Path loss factor A	1000
Noise power N_0	-103 dBm
Coverage angle $\hat{\delta}$	$\pi/2$
Attenuation factor Λ_α	0.1
Attenuation factor Λ_β	0
Attenuation factor Λ_γ (when spectrum not shared)	0

overall network capacity. Spectrum sharing can grant a higher capacity gain, but the combination of both also leads almost to superimpose the two benefits.

In addition, the improvement achieved through sharing is more pronounced when the networks deploy more relays. As regards the impact of the number of UEs per network, we observe that while the gain from spectrum sharing tends to decrease when the network is high loaded, mostly because both the frequency bands are almost fully-utilized, the capacity via relay sharing continues to grow, since spatial diversity is exploited at most when several UEs are deployed.

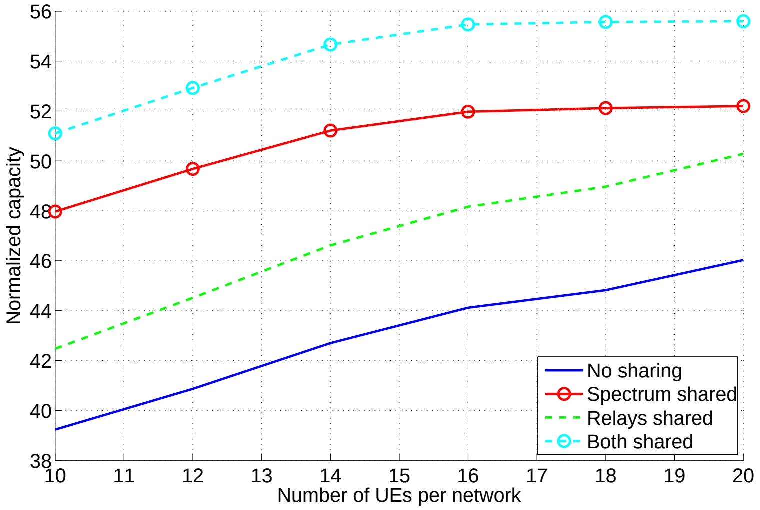

Figure 2.4: Normalized capacity of the four sharing options, for different numbers of UEs, with $k = 2$ relays per network. Both the networks have the same number of UEs and of relays.

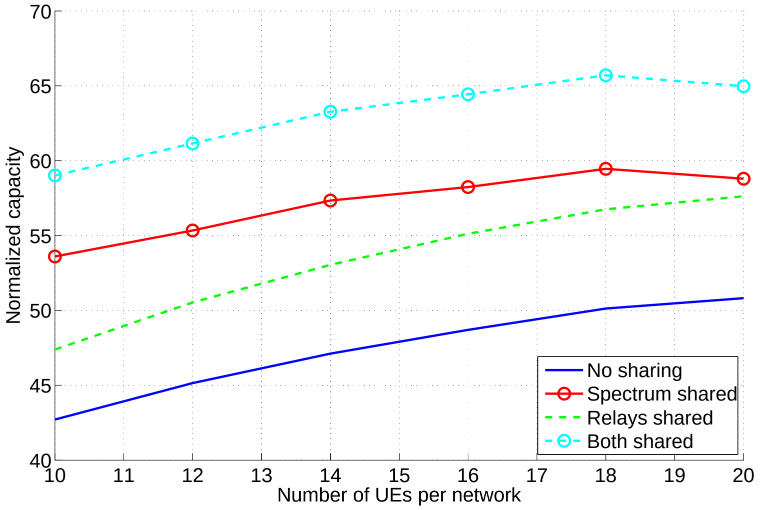

Figure 2.5: Normalized capacity of the four sharing options, for different numbers of UEs, with $k = 3$ relays per network. Both the networks have the same number of UEs and of relays.

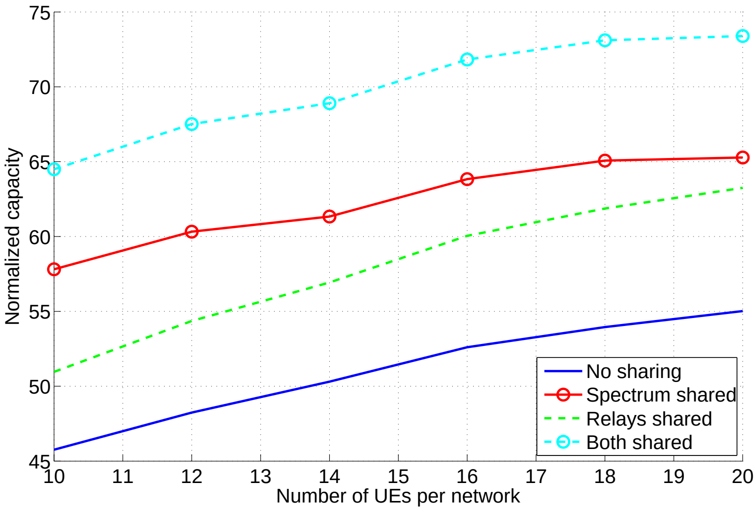

Figure 2.6: Normalized capacity of the four sharing options, for different numbers of UEs, with $k = 4$ relays per network. Both the networks have the same number of UEs and of relays.

3 Relay sharing: protocol design

To verify the evaluation of the previous section, we also need realistic protocol to approach that gain. Therefore we especially focus on relay sharing and its implementation in realistic networks. The allocation algorithms described in the previous section rely on the knowledge of the geographic positions of all the UEs and relays. In order to be implemented, the whole topology information must be gathered and processed by a single entity, and the resulting allocation scheme must be broadcast back to all the mobile terminals. Clearly, the particular structure of the investigated networks suggests the BS as the ideal candidate to execute the allocation algorithm.

In practice, however, all these steps require some overhead, which has an impact on the network performance. In addition, decoding errors can also reduce the amount of information available to feed the allocation algorithm, which may in turn determine a throughput loss. Aim of this chapter is to propose protocols which are able to perform the operations required in order to efficiently allocate the UEs of the network and fully exploit the infrastructure sharing.

Allocation is a key point even in a scenario consisting of a single network. However, since we are interested in resource sharing, we will design these protocols also for the case where two wireless networks coexist.

3.1 Scenario description

Each network consists of one BS, k relays and N UEs, and the topology is as described in Section 2.1. In addition, as a case study, we consider that the processing gain N_s is here due to the use of CDMA. A comparison will be successively carried out with a Single Carrier Frequency Domain Multiple Access (SC-FDMA) like scenario, where each UE is assumed to transmit on a different (pre-assigned) frequency, such that $N_s = 1$, but interference can be ignored.

In a real scenario, data are transmitted in packets, which are generated at the UEs. Therefore, we consider that time is slotted, and slot synchronization is assumed at each node. Each UE is a data source, and generates packets for the corresponding BS; packet generation is modelled as a Poisson process of intensity λ. The packets are considered of fixed length, and they can be transmitted in w slots. As a consequence, each packet is first divided into w sub-blocks; each sub-block is then added a short training sequence for channel estimation purpose, and a CRC for error detection, and is finally Binary Phase-Shift Keying (BPSK) modulated, spread with the assigned code, and transmitted within a single time slot. The first block also contains the header of the packet, which specifies its sequence number, its source, its destination and its intended next hop receiver.

The channel between a source S and destination D is modeled taking into account not only the path loss (with parameters A and α as in Section 2.1), but also shadowing and fast fading effects. While the former is kept fixed during the simulation, and modeled via a lognormal random variable $\omega_{s,d}$ with variance σ^2, the latter is represented by a complex Gaussian random variable $h_{s,d}(t)$ with zero mean and unit variance. It follows that, if P_{tx} is the transmitted power and $d_{s,d}$ is the distance between the two nodes, the received power P_{rx} at time slot t at the receiving node can be computed as

$$P_{rx} = \frac{P_{tx} d_{s,d}^{-\alpha}}{A} \omega_{s,d} |h_{s,d}(t)|^2 \tag{3.1}$$

Both shadowing and fading are independent between different users, but we consider a time-correlated fading channel, with correlation factor ρ between two subsequent time slots, such that

$$h_{s,d}(t+1) = \rho h_{s,d}(t) + \sqrt{1-\rho^2}\xi \tag{3.2}$$

where ξ is also a Gaussian random variable of zero mean and unit variance.

At the receiving side, we employ a CDMA-based MUD receiver. We use the following simplified decoding model. The SINR of the i–th signal, if we define $P^{(i)}$ as the corresponding received power, is given by:

$$SINR_i = \frac{N_s P^{(i)}}{\sum_{j \neq i} P^{(j)} + N_0} \tag{3.3}$$

where N_0 is the noise power. The Bit Error Rate (BER) is defined as $Q(\sqrt{SINR_i})$, where $Q(\cdot)$ is the complementary cumulative distribution function of the Gaussian distribution. If the sub-block contains b bits, the overall packet decoding probability can be derived from the Block Error Rate (BLER) as $(1 - Q(\sqrt{SINR_i}))^{wb}$. By applying this scheme to all the received signals, and assuming that the spreading codes are known, a receiver may be able to decode multiple concurrent transmissions.

As an option, we also allow the use of SIC at the receiver side [13], which we model as follows: the perceived signals are sorted based on their SINR. If the signal is correctly decoded, its contribution is subtracted from the heard signal, the remaining SINRs are recomputed, and the process is repeated. If on the contrary a decoding failure occurs, the procedure simply proceeds with the following highest SINR, without interference cancellation. The CRC bits associated with each block let the receiver node know whether the block was successfully decoded or not. The SIC model adopted is quite simple, since it implies that signals are perfectly cancelled, which is not true, in real systems. Therefore, we expect to derive performance upper bounds in the simulation results.

If FDMA is used instead, the SINR becomes a simple Signal-to-Noise Ratio (SNR), due to the orthogonal separation among users, and the decoding probability is simply obtained as $(1 - Q(\sqrt{SNR_i}))^{wb}$, with $SNR_i = P^{(i)}/N_0$.

Since multiple packets may be generated in a low amount of time (in high load scenarios), each UE has a queue where packets can be stored. Each queue can contain up to q packets, and a FIFO policy is adopted to determine the next packet to be transmitted. We also assume that each UE knows its geographic location. This assumption, however, may be relaxed, to consider only a partial geographic knowledge.

As regards the relays, they also have a queue, where the packets received from the UEs, which are to be forwarded to the BS, are stored. Relays are considered to be half-duplex, with directive antennas, as those described in Section 2.1. They are able to transmit on both the frequency bands, when they are shared between the two networks. For their transmissions, they are allowed to superimpose more than one (and up to M_{pkt}) packet, according to their queue status, provided that all the superimposed packets were received from different UEs. If this is the case, for each superimposed packet the relay uses the spreading code of the source UE of that packet. The power is equally shared among all the transmitted packets, and the adopted power allocation model is the one introduced in Section 2.1.

We also introduce a feedback–based superposition policy. Assume that n packets have been superimposed during a forwarding phase: if all of them were successfully received, then up to $\min(n+1, M_{pkt})$ packets can be combined in the following forwarding phase. Otherwise, up to $\lfloor n/2 \rfloor$ will be superimposed. This policy, if the relay is shared, is applied separately for the packets of each network, although the relay power is to be divided equally among all the packets, and the overall maximum number of packets that can be superimposed is still M_{pkt}.

Since we are interested in Uplink transmissions, we consider downlink channels only for control packets. More specifically, we assume that each BS/relay has its own dedicated DL channel (either a specific code, for CDMA, of a specific frequency band, for FDMA), which is known at every UE. Therefore, simultaneous transmissions from multiple relays can be received by the UEs. As will be clarified later, UL and DL transmissions are separated in time.

3.2 Coordinated network

In this section, we consider a *coordinated* scenario where the transmission scheduling is fixed throughout the whole network. This means that each time slot is dedicated to a specific transmission, according to a predefined cyclic scheme. While data packets are transmitted over w time slots, signalling packets, on the contrary, are much smaller, with a transmission duration of only one slot. Moreover, given their key role, they are protected by a simple repetition code of rate 1/2 to guarantee a higher decoding probability.

This kind of network is highly organized. On the one side, the global scheduling grants a very efficient utilization of the resources, by parallelizing transmissions and avoiding unnecessary interference, in the steady state. On the flip side, the time required for a single UE to be allocated may be longer, due to the fact that the slot utilization scheme must be followed.

The main idea behind the proposed protocols is to let the UEs transmit their packets, which are then acknowledged by either the relay or the BS (depending on the UE allocation). After this phase (of duration $w + 1$), some slots are left free for UL and DL signalling. The number of these slots, as well as their utilization, depends on the type of allocation desired. In fact, collecting local information is faster and requires less resources, but may also result in a less efficient allocation. We now proceed to illustrate two kind of protocols: the former aims at determine the UEs allocation based on local information, while the latter tries to collect all the necessary information to the BS, where the allocation is computed by means of the algorithm proposed in Section 2.3.3.

3.2.1 Protocol based on local parameters

A scheme where allocation is based on local information is introduced here. We first describe how this protocol works when implemented by a single network, and then we explain how it can be extended for the case of two co-existing networks which exploit infrastructure sharing.

The main idea behind the *LAB* (Local Allocation Based) protocol is to reduce the amount of overhead by letting the UEs select the best node (BS or relay) to be allocated to. In order to achieve the result, each UE needs to broadcast some information about its location, and successively to collect feedback from the surrounding relays/BSs. UEs far from the BS are likely to choose a relay, but also in this case the decision is made locally, with only a minimum overhead to be sent to the BS.

In the proposed protocol, a UE p can join the network upon exchange of two signalling packets, namely Allocation Request (AR) and Allocation Information (AI). The AR packet (Allocation Request) is first broadcast by the UE, and contains its geographic location, as well as other information which may be useful (for instance, the amount of data to be transmitted, or the desired Quality of Service (QoS)). We assume that it can be sent within a single time slot. If only one network is deployed, or if resource sharing is not implemented, only the BS and the relays belonging to the same network are allowed to reply in the following time slot with an AI packet. This packet contains the information about the relay/BS to be used by the UE to determine its allocation. There are different choices, including:

1. the geographic position or the relay/BS;
2. the current load of the relay/BS in terms of number of UEs already allocated to it;
3. the current buffer occupancy (for relays only);
4. expected SINR of the transmission coming from UE p, based on the channel estimation performed during the AR transmission.

A combination of these factors can be reported as well. Notice that adopting the first and/or the second choice results in applying a distributed version of the *GEO* and *GEO-L* algorithms designed in Section 2.3.1 and 2.3.2.

In addition, the AI may be sent only by those relays for which a given condition about the SINR of the received AR is met. For instance, only relays which received the AR with a SINR higher than a given threshold are allowed to reply with the AI, in order to save power and reduce the overall interference in the cell. In the AI packets, additional information can be stored, such as the channel (code/frequency) the UE has to transmit on. Each relay is assumed to handle a subset of channels, to be assigned to UEs allocated to it; a relay which is already using its entire subset

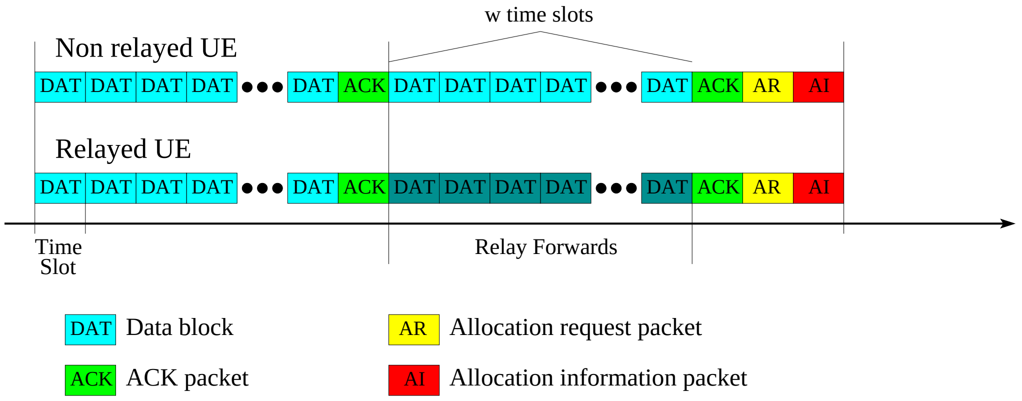

Figure 3.1: Time slot scheduling for the protocol with allocation based on local parameters. Utilization of the time slots is shown for both relayed and non relayed UEs. Here $k_r = 2$.

of channels simply does not reply with AI packets. Notice that a relay which is not sending a AI can listen to the one transmitted by the BS, which in turn can use it to assign new channels to overloaded relays.

Upon reception of multiple AI's, the UE is informed about the surrounding relays/BSs to be allocated to, and can perform its choice, depending on the parameter of interest. The ID of the selected station is therefore set in the header of the following packet. The time between two subsequent slots dedicated to AI transmission is called a *cycle*, and the corresponding number of slots is called ℓ_c. Within each cycle, k_r sequences DATA–Acknowledgement (ACK) are performed, as clarified in Figure 3.1. Each sequence consists in the transmission of a packet from a UE or a relay, followed by an ACK sent by the intended receiver, which declares the correct decoding or requires a retransmission. If a UE is allocated to the BS, it can transmit up to k_r packets in each cycle. If, on the contrary, it is allocated to relay, then it can transmit up to $k_r/2$ packets in a cycle. In fact, half of the time is reserved to relay transmissions. It follows that k_r should be an even number, although this is not strictly necessary. The overall slot utilization is reported in Figure 3.1. In the upper part, the sequence of packets transmitted in the network for the case of a UE allocated to the BS is reported. In the lower part, the same is done for the case of a UE whose packets are forwarded by a relay.

When the packet is not successfully decoded at the intended receiver, that packet is stored in the transmitter buffer, in order to be retransmitted in the next allowed slot. Depending on the amount of information contained in the ACK, two feasible solutions can be adopted:

- if the ACK simply feeds back the success or failure of the packet decoding, then the entire packet is retransmitted (in this case, the CRC is needed only in the last packet fragment);
- if the ACK contains information about the successful decoding of each packet fragment, then only the missing fragments can be retransmitted, possibly with repetition, in order to fully occupy the available slots and to exploit time

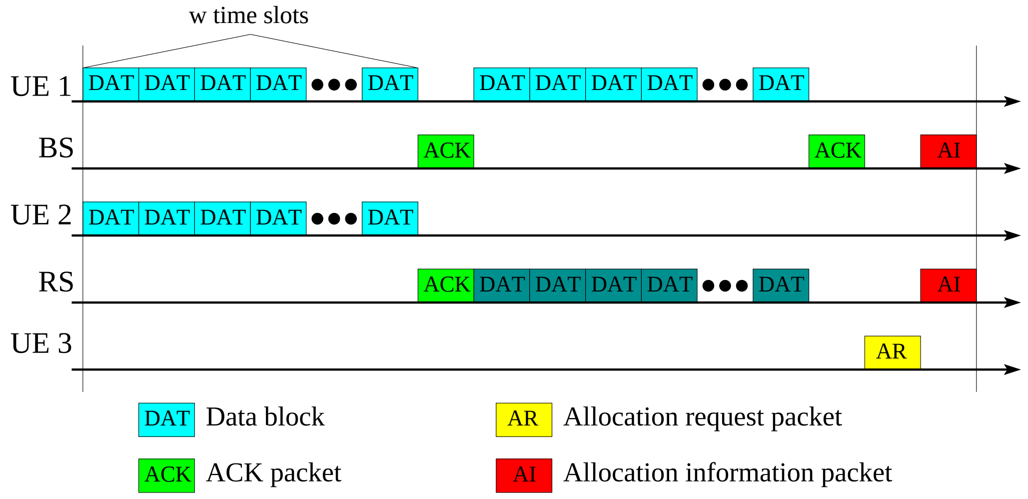

Figure 3.2: Time slot scheduling for the protocol with allocation based on local parameters, with $k_r = 2$. UE 1 is allocated directly to the BS, UE 2 is helped by the relay RS, whereas UE 3 still has to determine its own allocation.

diversity.

The first solution requires a much smaller packet, which can be relevant, since the BS and the relays may have to acknowledge multiple packets at the same time. The second one, however, can strongly reduce the number of required retransmissions. The retransmissions are in any case limited to a maximum number of trials M_{tx}, after which the packet is discarded. In this work, we focused our attention to the first approach.

It can also happen that, after an AR broadcast, no AI is received or decoded. In this case, a new attempt is performed in the next slot dedicated to AR transmission.

The values of w and k_r are to be carefully chosen. Both can be increased, in order to reduce the amount of overhead. However, a higher value of w leads to a greater decoding failure probability, while k_r influences the amount of time required for a UE to obtain its allocation and join the network.

An example of how the transmissions are performed is reported in Figure 3.2, where $k_r = 2$: UE 1 is allocated to the BS, and can consequently transmit two packets within each cycle; UE 2, on the contrary, is allocated to a relay (Relay Station (RS)), and its packet must be forwarded, resulting in a single packet per cycle. Finally, UE 3 wants to join the network, and therefore sends the AR at the end of the cycle, waiting for the AI's coming from the BS and the relay(s). Notice that the relay sends only one ACK per cycle, differently from the BS, which has to acknowledge all the packets not forwarded by any relay.

So far, we have illustrated how the protocol works within a single network. We now extend the description to include the case where two co-existing networks decide to share their relays. We limit our analysis to the case of infrastructure sharing, which means that the two networks keeps exclusive control of their own frequency bands, which we call f_1 and f_2. As discussed in Section 2.2, a particular attention is to be put on how the frequencies are handled. We choose to adopt the scenario with a double–frequency backhaul link, meaning that the relays only are allowed to receive and transmit on both the frequencies. This means that the choice of sharing the relays or not is transparent to the rest of the network (UEs and BSs), in terms of physical layer equipment.

The differences with respect to the case with no sharing are the following ones:

- the relays listen for AR packets on both the frequency bands; correspondingly, they reply with the AI packets on both f_1 and f_2, with their power equally shared between the two frequencies. This implies a lower transmission range, but in most cases the power allocated on each band is still equal or greater than the power used by the UE for the successful AR: this should guarantee that the AI packets are also decoded;
- a UE can choose a relay of the other network for packet forwarding. The transmission on the access link is performed by the UE on its predefined band, as well as the transmission on the backhaul link. It follows that a relay chosen by UEs of both the networks is required to transmit on both f_1 and f_2. The power is allocated as in the case of non cooperating networks.

The main advantage given by the relay sharing lies in the augmented diversity. In fact, each UE is likely to have more choices for a relay-aided transmission. When several relays per network are already deployed, this effect is more pronounced if shadowing is taken into account. A second important consequence which is to be considered is that a shared relay may send packets on two different frequency bands. This is beneficial, since when several packets are combined together and sent to the same BS, at the receiver they are all received with the same power, which is not the optimal situation for applying Interference Cancellation. When a failure occurs, a non shared relay has to reduce the number of combined packets in the following packet transmission phase. A shared relay, on the contrary, can use the remaining power to send packets to the other BS, thus efficiently exploiting each single transmission.

3.2.2 Protocol based on global parameters

Protocols based on local parameters show a clear advantage in terms of reduced overhead. However, they suffer from the partial knowledge available at the BS. In fact, if for instance the allocation is based on both the geographic position and the relay load (in terms of already allocated UEs) it may occur that a UE which joins the network is forced to be helped by a high loaded relay; a redistribution of the other UEs would be beneficial, but cannot be done, unless a global re-allocation is performed.

This consideration motivates the proposal of a protocol which lets the BS decide how to allocate all the users. Variations in the topology can be handled more easily, and centralized algorithms can be implemented. On the flip side, the main problem, even when we consider a single network, is that the allocation request of each UE must be delivered to the BS, with a two–hop path, if needed. Similarly, the allocation computed by the BS must be broadcast to all the relays and the

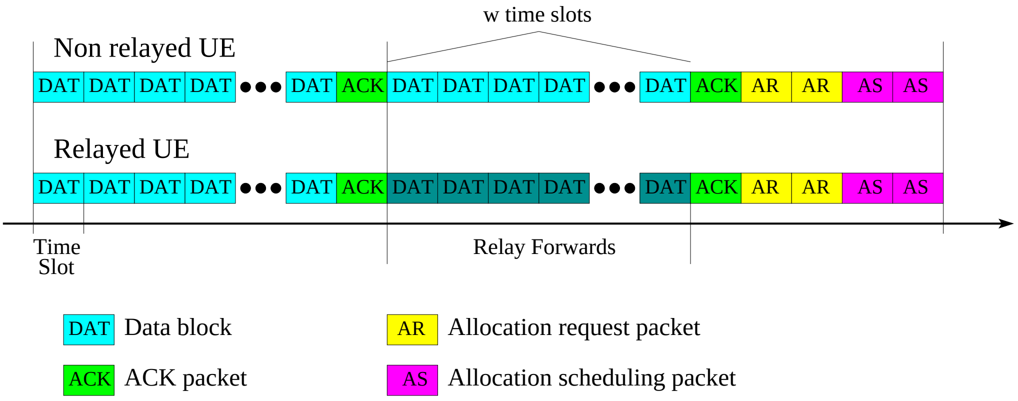

Figure 3.3: Time slot scheduling for the protocol with allocation based on global parameters. Utilization of the time slots is shown for both relayed and non relayed UEs. Here $k_r = 2$, and the AS packets are forwarded by the relays.

UEs. Although the BS can transmit with a much higher power, decoding errors become more frequent for cell edge users (also because inter-cell interference can additionally degrade the SINR).

The general structure of the *GAB* (Global Allocation Based) protocol is the same of the *LAB* protocol, and is based on DATA–ACK sequences collected in a cycle. The allocation phase in instead different. When a new UE joins the network, it again broadcast a AR packet, including information about its position, the amount of data to be uploaded, the required QoS and so on. The relays which decode the message, however, do not reply with a AI message, but instead forward the AR packet to the BS. If more AR are received, they can combine the information contained in them within a single AR, although this occurrence is quite rare, if k_r is not too high. The BS then collects all the AR packets, either coming directly from a UE or being relayed. Having gathered all the necessary information, it can then use a centralized algorithm, like those designed in Section 2.3, to properly assing each UE to a relay (or to itself). At this point, it creates a Allocation Scheduling (AS) (allocation scheduling) packet, containing all the information about the allocation for the UEs which joined the network and/or about the UEs which are required to change allocation, due to a topology change. The AS packet can be forwarded by the relays or not, depending on the protocol design. The slot utilization for the *GAB* protocol is shown in Figure 3.3.

As seen for the *LAB* protocol, the choice of w and k_r plays a key role in determining the delivery probability of a packet and the allocation speed. In addition, different allocations can be computed here, depending on the adopted algorithm at the BS. Referring to the ones defined in Section 2.3, some possible choices are the following:

1. geographic allocation: as seen before, the UEs can be allocated to the closest BS/relay (*GEO* algorithm);

2. load-based allocation: the UEs are equally shared among the available relays (*GEO-L* algorithm). This is particularly useful when the backhaul link is not

particularly good, as the queues at the relay may become long. However, in the scenario investigated, this choices may lead UEs to use bad channels, resulting in poor performance;

3. capacity-based allocation: an algorithm which maximizes the overall network capacity, as the *CBA* algorithm described in Section 2.3.3, can be employed. However, depending on the particular scenario, maximizing the capacity may not correspond to maximize the effective throughput.

4. throughput-based allocation: an algorithm which minimizes the error probability over the selected links, like the *TBA* algorithm, can be used to obtain a higher network performance in terms of throughput or delivery delay.

Clearly, different metrics can be chosen, and correspondingly, different algorithms can be implemented [10]. It must be considered however that, due to the multi–hop transmission required for the AR and AS packets, information about instantaneous channel conditions, especially regarding the access links, may be outdated, and therefore less useful [4].

When two coexisting networks are deployed, the *GAB* protocols can exploit the double–frequency backhaul links to exchange information between the two BSs. In fact, when relays are shared, the allocation algorithm must be fed with the information about the UEs of both the networks. Therefore, in this case, the relays forward both the AR and the AS packets on both the frequency bands, equally sharing the power between them. By sending the AR packets on f_1 and f_2, each relay can inform both the BSs about the new UEs which are joining either one or the other network. The completness of the received information may be crucial in determining the best possible allocation. Also the AS packets are sent on both the frequencies. As discussed above, this forwarding is not necessary for a single network, provided that the transmission power of the BS is high enough. When two cooperating networks are deployed, however, there is an important difference. In fact, UEs close to the BS usually send AR packets which are not received by the relays (due to the directive antenna for the access link), but only by their own BS (since the other one operates on a different frequency band). As a result, the BS 1 would never be aware of the UEs directly communicating with BS 2. When BS 2 sends the AS packet, however, it includes also the IDs of these UEs. As long as this AS packet is forwarded by the relays on both f_1 and f_2, also BS 1 is informed of the presence of these UEs, and can use this information to correctly compute the best allocation. An example of how the allocation information is conveyed to the nodes of both the networks is reported in Figure 3.4.

3.2.3 Opportunistic routing

When CDMA is used, unless some sort of power control is adopted, the main limit of the network is interference. In fact, regardless of how the UEs are allocated to the relays and the BSs, the amount of interference does not almost change at every receiver. For the same reason, however, the same signal can be received, and decoded, by a number of nodes in the network. Instead of treating these signals as

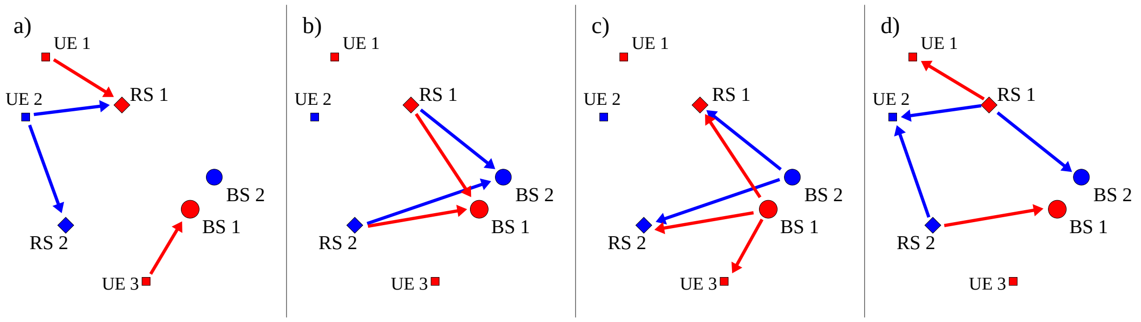

Figure 3.4: Allocation scheme for the *GAB* protocol, with AS forwarding. In a), the UEs send the AR packets on their own frequencies, while the relays listen on both; in b), the relays forward the AR packets to the BSs, and they all transmit on both the frequency bands; in c) the BSs, after having computed the optimal allocation, send the AS packets on their own frequencies; finally, in d), the relays forward the AS packets. Notice that the forwarded AS packet sent by RS 1 makes BS 2 aware of UE 3, which would have otherwise remained unnoticed by the BS of the blue network.

interference, it is possible to take advantage of the broadcast nature of the medium, to exploit the so called *opportunistic routing* [3]. In principle, instead of setting up a route for each UE, it would be possible to let them transmit, and then exploit, as a helper, the relay(s) which correctly decoded the packet. This approach would be much more flexible than a predefined allocation, since it would be able to adapt to the channel conditions, and to achieve the highest benefit from spatial diversity. On the other side, however, signaling packets would be required to avoid unnecessary transmissions of the same packet from multiple sources, or to set up a coordination between different transmitters.

We explore this approach by modifying the *GAB* protocol into the *OAB* (Opportunistic Allocation Based) protocol. The main idea is that any UE has a default allocation. This allocation is set up as in the *GAB* protocol, and we keep it for two reasons: firstly, this is the preferred allocation, used also for DL signaling and channel assignment; secondly, it is useful make opportunistic routing easier. In fact, only UEs whose default allocation is a relay can take advantage of opportunistic routing. The reason for this is that the relayed UEs and the relays always transmit DATA in different time periods, while this does not hold for the UEs using the direct links. Say that UE i has its BS as preferred allocation. If a transmission fails, and a relay is instead able to decode the packet, it would put the packet into its queue, and could retransmit it later. In this case, however, it would be necessary to warn the UE about this retransmission, since it is performed on the same channel (code or frequency) used by the UE, and this would cause a collision. The only way to avoid additional signaling would be to let the relay use a different channel among those still available to it.

We then prefer to limit opportunistic routing to relayed UEs only, where, due to the strong backhaul links, it is easier to organize transmissions such that the default relay and the opportunistic one do not transmit DATA from the same UE simultaneously, without need for additional channels.

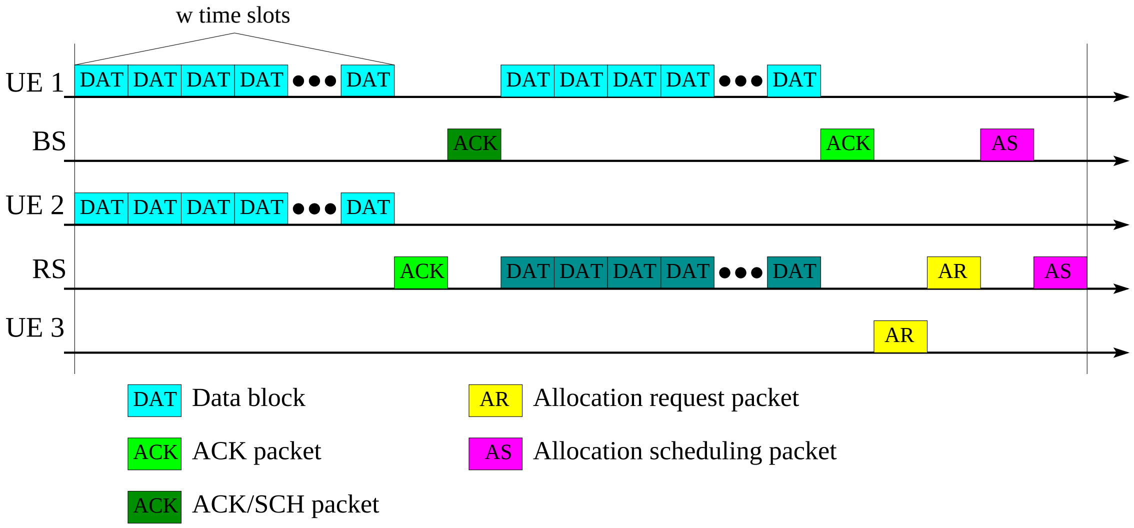

Figure 3.5: Time slot scheduling for the *OAB* protocol. UE 1 is allocated to the BS, whereas UE 2 is allocated to a relay. After the relays send the ACK packets, the BS transmits the ACK-SCH packet, in order to allow opportunistic forwardings and avoid collisions. UE 3 has just joined the network, and uses the AR packets to retrieve its default allocation.

From a design perspective, the only difference with respect to *GAB* protocol is that, after the first DATA transmission phase, only the relays send the ACK packets, and to both the UEs and the BSs. They indicate the ID of all the received packets, regardless of their intended destination. The BS, upon reception of the ACK packets, is able to recognize if a packet which was not successfully received by the default relay was instead decoded by another relay (or by itself). In the following time slot, the BS sends a ACK–SCH packet, where it acknowledges the received packets (as in the *GAB* protocol), and also assigns to the relays the right to forward opportunistically decoded packets. In doing this, the BS also verify that no collision occurs between the default relay and the opportunistic one, by letting only one of them to send DATA from the common source. After this slot, everything proceeds as in the *GAB* protocol. A scheme of the slot utilization of the *OAB* protocol is depicted in Figure 3.5.

The *OAB* protocol extension to the scenario with two coexisting networks is straightforward; the BSs still send the ACK/SCH packets on their frequencies, since the relays can listen on both f_1 and f_2, and behave exactly like a BS of the same network of the BS which is sending the packet (the double–frequency backhaul link makes the relay sharing almost transparent to both BSs and UEs). The use of opportunistic routing, despite the need for a higher amount of overhead, can be especially beneficial in scenarios where relays are shared. In fact, a higher density of available relays increases the probability that the signal sent by a UE (especially far from the BS) is correctly decoded by at least one relay.

3.2.4 FDMA networks

The same protocols illustrated above can be applied in a different kind of scenario. For the purpose of comparison, we present the performance of *LAB* and *GAB* protocols in a scenario where FDMA is used instead of CDMA. This scenario can be easily obtained from the previous one by simply put $N_s = 1$ and ignoring interference in the SINR expressions of Section 2.1. In this case, every UE is assigned a different frequency to transmit on. We consider orthogonal frequencies, but we do not consider frequency reallocation based on channel conditions, since this would require a frequency-allocation algorithm which is beyond the scope of this work. Clearly, such an algorithm would further increase the performance of the network, although at the cost of additional overhead, necessary to collect all the information about the channel state.

The FDMA network is no longer interference-limited. It follows that the main gain of relay sharing is due to the fact that a closer relay may be available, thus increasing the decoding probability. *LAB* or *GAB* protocols based on distances (modified to keep shadowing into account) work best, under the assumption that the backhaul link is strong enough. Otherwise, also the load of the relays should be considered, aiming at reducing the length of the queues. Relays can still superimpose packets, by transmitting on different carriers at the same time. However, the use of opportunistic routing may be too heavy in this case, since it would require the relays to listen to the whole set of carriers, searching for signals coming from other UEs. This is why we do not consider opportunistic routing in this case.

3.2.5 Simulation results and comparison

In this Section, we present some results obtained through the application of the proposed protocols in a scenario where two relay-aided wireless networks are deployed. Non orthogonal relay sharing is taken into account, and the corresponding throughput gain is analyzed. The results are based on MATLAB simulations, where, for each scenario, 50 randomly deployed topologies are considered, both with and without relay sharing. The specific parameters used in the simulations are listed in Table 3.1. The aggregated throughput is calculated as the global number of received packets at the two BSs, divided by the total duration of the simulation (in seconds). In general, we are interested more in the gain achievable with relay sharing than on absolute values. This is why we focus our attention on the ratio between the achieved throughput with and without resource sharing. Clearly, the usage of specific technologies, like SIC, grants higher performance for both the sharing and non-sharing scenario.

Given the huge number of parameters, a complete investigation would require a very wide simulation campaign. In the present deliverable, we fix most of the parameters, and put our attention to those which may affect the throughput gain granted by the sharing of relay nodes. We focus on both CDMA-like and FDMA-like networks; in the former case, we observe the impact of Interference Cancellation and of Opportunistic routing.

For each specific scenario, we plot the minimum and the maximum throughput

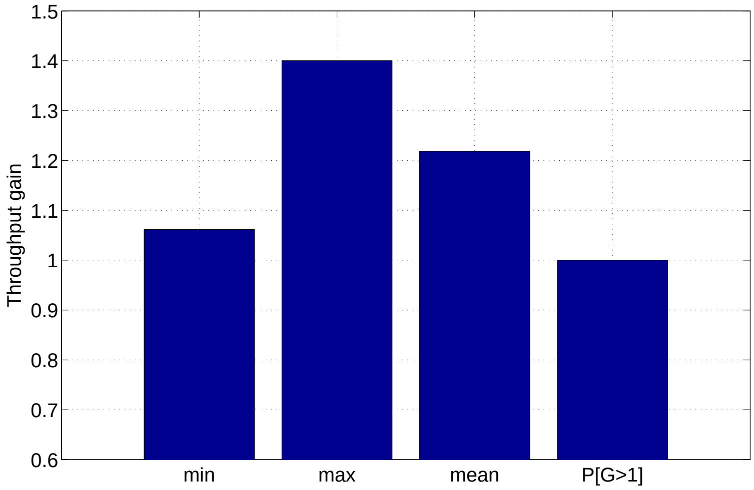

Figure 3.6: Throughput gain in a CDMA scenario, without SIC. Allocation is done via the *GAB* protocol, implementing the GEO allocation algorithm.

gain observed over the 50 random topologies. We also plot (last bar) the mean gain and the probability that the ratio between the throughput with and without relay sharing is greater than 1 (that is, the probability that there is an actual gain).

We first observe the effect of relay sharing in a CDMA scenario, where SIC and OR are not employed. The *GAB* protocol is used, and hence the allocation is computed by the BSs in a centralized fashion. The adopted algorithm is the *GEO* algorithm, which tries to minimize the length of the activated links. In Figure **??**, the minimum, maximum and average throughput gain are reported. The results show that in all the tested topologies a throughput gain was observed: this gain varies from a minimum of 6% to a maximum of even 40%, with an average gain of 22%. Such a gain is mainly due to the fact that cell-edge UEs, without power control or SIC, has almost no probability of successfully transmitting to a far relay/BS. The increased number of available receivers makes it easier to find a closer node available for packet forwarding.

The GEO allocation scheme can be applied also in a distributed fashion, by means of the *LAB* protocol. Since the *GEO* allocation based on transmitter-receiver distance does not require any global information about the network topology (differently from the *GEO-L* allocation), the *LAB* protocol can offer higher throughputs, due to the lower amount of overhead. This is in fact what was observed via simulation in the CDMA scenario. The throughput was increased, with respect to *GAB* protocol, of about 12%–15%, both with and without relay sharing. We report the sharing gain in Figure 3.7: a maximum throughput gain of 60% was observed, with an average gain of 25%.

As discussed above, in an interference-limited scenario, where there is no orthogonal separation among users, the geographic allocation may not be the optimal one, since also the interference must be taken into account, and hence the overall SINR over the activated links. Therefore, we tested the same scenario where, however, the

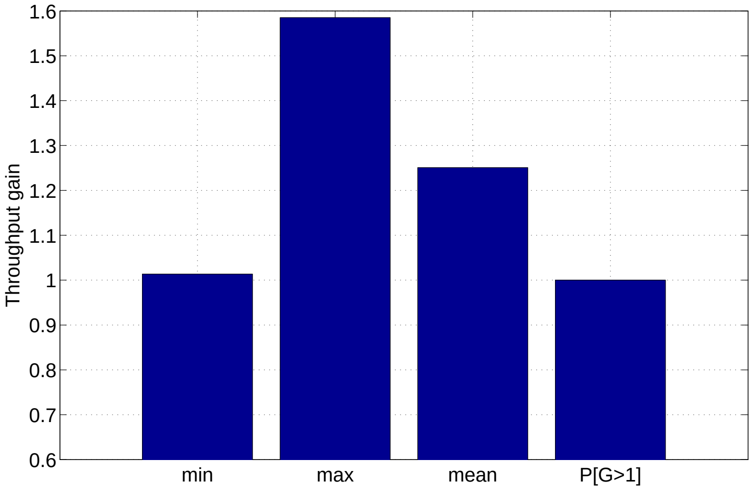

Figure 3.7: Throughput gain in a CDMA scenario, without SIC. Allocation is done via the *LAB* protocol, implementing the *GEO* allocation algorithm.

CBA algorithm was adopted to select the best allocation. No significant variations were observed, in terms of absolute throughput values. This is mainly due to the fact that ignoring the effects of fast fading, as done in the *CBA* and *TBA* algorithm, degrades the effectiveness of the algorithm itself. More refined indicators, such as the outage probability for every user, should be instead computed, based on the channel fading statistics. However, due to the presence of simultaneous transmissions, the outage probability for every channel is hardly derivable, being the involved random variables quite correlated with each other. This investigation is hence left for future work.

Figure 3.8 compares the throughput in the CDMA scenario, with the *CBA* allocation algorithm implemented via the *GAB* protocol. We notice that, again, an improvement is obtained in all the considered topologies, with a minimum gain of 4% up to a maximum of even 62%. The average gain is 30%, again mainly due to the presence of closer relays, where signals from cell-edge users have a higher probability of being decoded.

For comparison, we also tested the *TBA* algorithm, which appears to be less effective, as shown in Figure 3.9. In fact, although there are some cases in which the throughput can be even doubled by using the relays, in other topologies the resource sharing proved not to grant any benefit. The average throughput gain was 36%, but in the 4% of the considered cases, a throughput loss was instead observed.

The main problem with both the *CBA* and *TBA* algorithm is that it is not easy to characterize the network in an effective and simplified manner. The average SINR is not enough to determine the quality of the selected allocation, since it does not take into account a number of aspects, like the channel time correlation (which affects the retransmission numbers and the error probability), the queue length, the loss of control packets, and so on. Further refinements are hence needed.

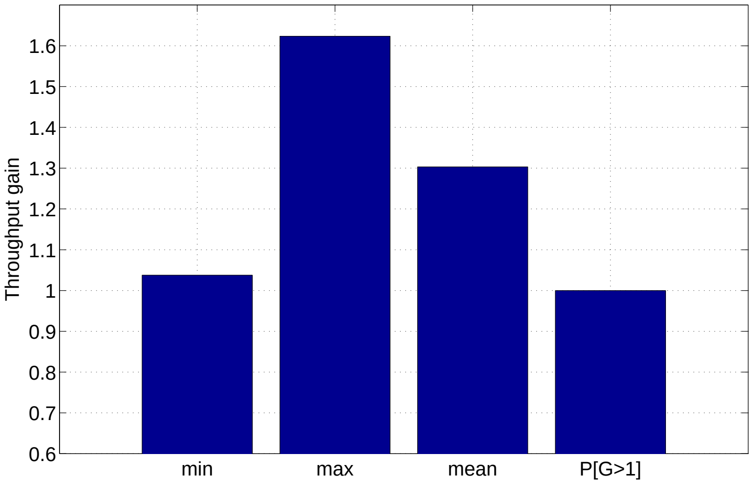

Figure 3.8: Throughput gain in a CDMA scenario, without SIC. Allocation is done via the *GAB* protocol, implementing the *CBA* allocation algorithm.

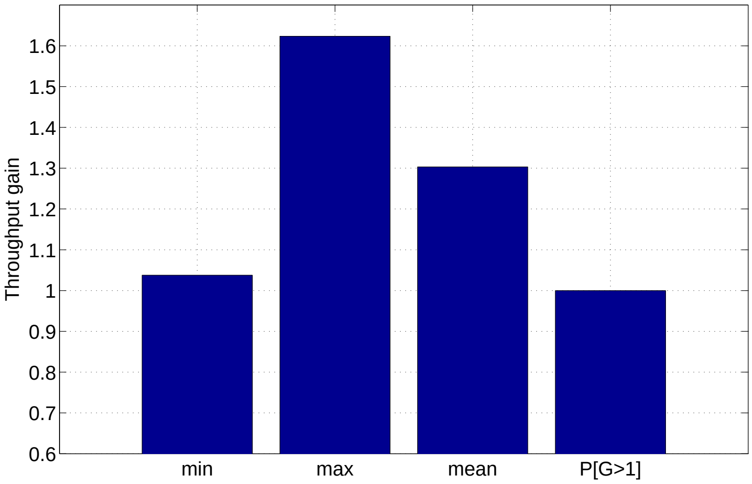

Figure 3.9: Throughput gain in a CDMA scenario, without SIC. Allocation is done via the *GAB* protocol, implementing the *TBA* allocation algorithm.

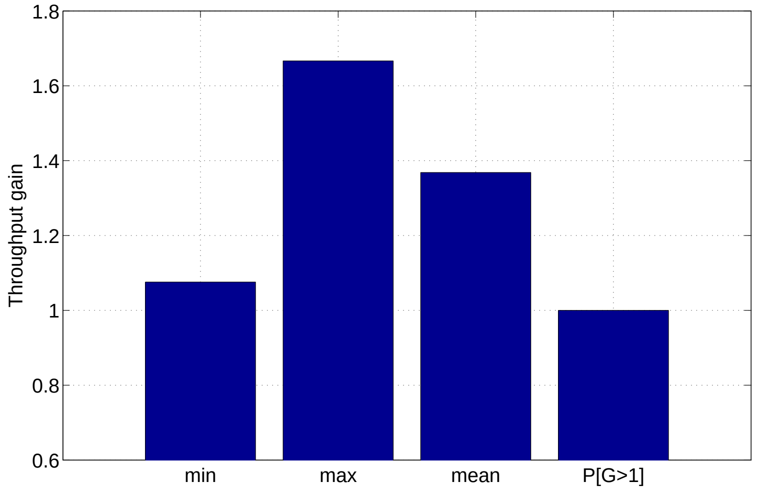

Figure 3.10: Throughput gain in a CDMA scenario, without SIC, when Opportunistic Routing is allowed. Allocation is done via the *OAB* protocol, implementing the *GEO* allocation algorithm.

By looking again at the *GEO* algorithm, a considerable improvement can be obtained via Opportunistic Routing. In fact, due to the directional antennas designed for the access link, the probability for a cell-edge of finding two relays of the same network as possible forwarders is quite low, when the number of relays is limited. The same probability, however, is highly increased when the relays are shared with a second network. Correspondingly, the throughput gain is much higher, as proven by Figure 3.10.

The absolute value of the throughput, for the non-sharing scenario, is the same as when OR is not used, whereas, when resource sharing is enabled, it is increased of approximately 30%. As a result, the throughput gain, which was observed in all the tested topologies, is between 8% and 67%, with an average value of 37%.

When signal processing techniques are introduced, as intuition suggests, the throughput increases both if relays are shared or not. As a consequence, a higher amount of the network capacity is exploited, and the further improvement granted by infrastructure sharing is lower. In fact, if SIC is employed at the relays, even signals transmitted by far UEs have a higher probability of being decoded, thus reducing the need for a closer receiver. In Figures 3.11 and 3.12 we plot the throughput gain for the case where SIC is used, with and without OR, respectively. The *GEO* algorithm is used, implemented via the *GAB* protocol. When OR is not allowed, it is observed that relay sharing can grant a throughput improvement in the 92% of the cases. However, the gain is much lower than in absence of SIC, with an average value of 4% and a maximum of 13%. The use of OR, as before, increases the benefit offered by relay sharing, leading to a doubled average gain (8%). In this case, a gain was obtained in the 94% of the topologies, with a maximum value equal to 24%.

Finally, we compare the same scenario where FDMA is used instead of CDMA. In this case, SIC is useless, since we consider orthogonal frequencies, and hence

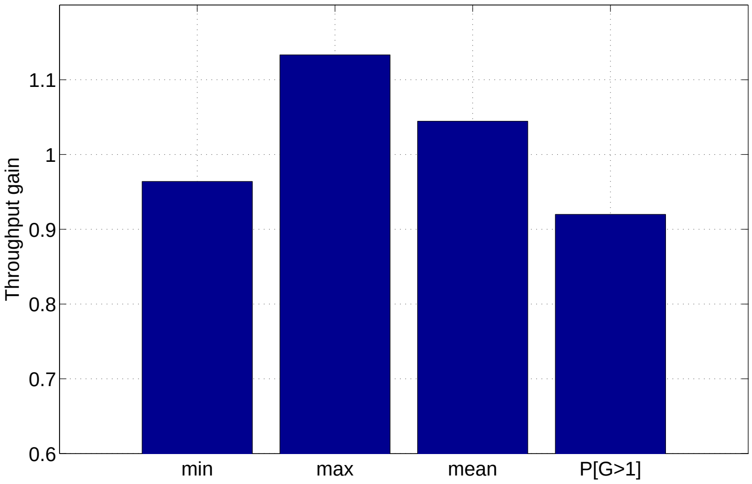

Figure 3.11: Throughput gain in a CDMA scenario, with SIC. Allocation is done via the *GAB* protocol, implementing the *GEO* allocation algorithm.

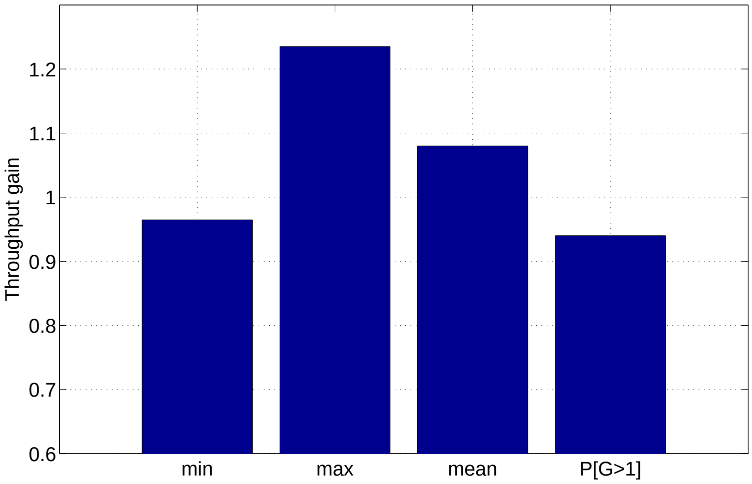

Figure 3.12: Throughput gain in a CDMA scenario, with SIC and Opportunistic Routing. Allocation is done via the *OAB* protocol, implementing the *GEO* allocation algorithm.

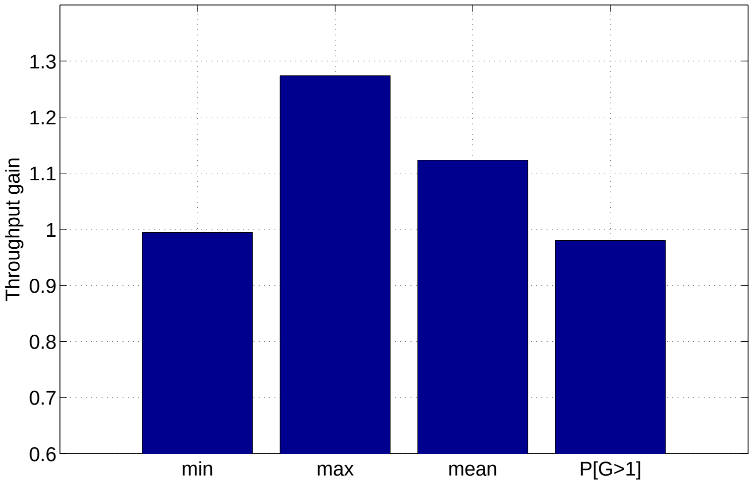

Figure 3.13: Throughput gain in a FDMA scenario. Allocation is done via the *GAB* protocol, implementing the *GEO* allocation algorithm.

interference is avoided. Since in this case the network is noise limited, the optimal choice for the allocation algorithm is the *GEO* algorithm, which is implemented via the *GAB* protocol. As expected, a gain is achieved in almost all the topologies (98%), with a maximum observed throughput increase of 27%, and a mean value of 12%, as depicted in Figure 3.13.

For comparison, we also present the sharing gain when the *GEO-L* algorithm is implemented via the *GAB* protocol. The relayed UEs are fairly distributed among the relays in this case. However, since the backhaul links are strong, the absolute throughput is similar, and some loss is instead observed with respect to the *GEO* approach, since some UEs are forced to transmit to farther relays. Figure 3.14 shows the throughput gain granted by relay sharing: a performance improvement is observed in the 96% of the topologies, the average is again 12%, with a maximum registered increase of 35%.

3.3 Ad hoc-like network

Most of the algorithms and protocols defined in the previous Section can be easily used also in an Ad Hoc-like network. In this kind of networks, we still assume that one Access Point (AP) (access point) and k relays are deployed in a given area, while N users tries to transmit their packets to the AP. If necessary, relays can help users far from the access point. We consider again a static network, where time is divided in slot, with the same parameters listed in 2.1. Differently from a cellular-like network, however, in this case there is no global transmission scheduling. It follows that, whenever a user has a packet to transmit, it must check the availability of the relay/AP it is allocated to. This is done via a Request To Send (RTS)–Clear To Send (CTS) handshaking between user i and the relay/AP.

The transmission mechanism between user i and node j is therefore the following:

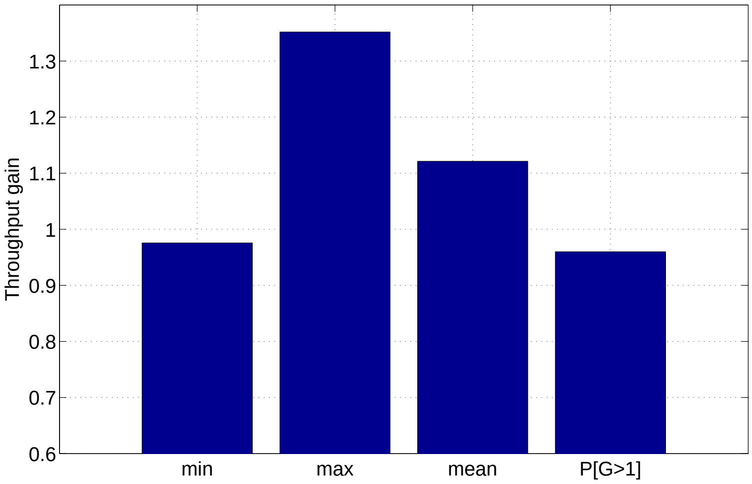

Figure 3.14: Throughput gain in a FDMA scenario. Allocation is done via the *GAB* protocol, implementing the *GEO-L* allocation algorithm.

1. user i sends a RTS packet to j, to ensure that it is not already involved in another communication;
2. if j is idle, it replies with a CTS packet, thus allowing i's transmission;
3. user i now transmits the packet, which, as before, is divided into w blocks, each one transmitted in a single time slot. A training sequence for channel state estimation and a CRC to check the presence of decoding errors are also added;
4. node j concludes the communication with an ACK packet, declaring whether the packet was successfully received or not;
5. if the packet was decoded, node i goes back to idle state, whereas node j enqueues the packet (if it is a relay) or passes it to higher layers (if it is the AP); if instead a trasmission failure occurred, a retransmission is scheduled after a randomly chosen backoff period. The packet is discarded if M_{tx} transmission attempts have failed (considering also missing CTSs).

If two networks are deployed, the users of each network transmit on their home frequency band, unless relay sharing is enabled. If this is the case, the relays can listen on both the frequencies. A main difference, with respect to the cellular-like scenario, is that a relay can never transmit towards both the APs at the same time. In fact, since the transmissions are not coordinated, it is unlikely that both the APs are idle at the same time, at least for loaded networks. Therefore, each relay can still transmit superimposed packets, if its queue contains more than one packet, but it has to combine only packets belonging to the same network (and, clearly, no more than one packet from the same user). This is a main limitation in this scenario, which severely degrades the effectiveness of relay sharing.

As in the cellular-like scenario, the users allocation is the key issue. We adopt the same solutions designed in Section 3.2.1 and 3.2.2, keeping in mind that much less coordination is now available.

3.3.1 Protocols based on local parameters

The *LAB* protocol relies on the local allocation selection performed by the user based on the information retrieved about the surrounding relays. Whenever a new user enters the network, it broadcast an AR packet, containing its geographic location, as well as any other information which may be used for allocation. Any relay (and AP) who receives the AR and is idle replies with the AI packets, which may include not only its location, but also the status of its buffer or the number of users already allocated to it. If more than one AI packet is received, the user can choose the best available relay, which will be the destination of its next RTS packet. Due to the lack of coordination, it may happen that the best available relay is communicating with another node when the AR packet is sent. This can lead to a suboptimal allocation. A way to limit this problem is to keep the users listening when in idle state, with the aim of receiving other AI packets sent by close relays to a new user which just joined the network.

When relay sharing is enabled, the only difference is given by the fact that the relays listen on both the frequency bands. Upon reception of a AR packet, they reply on the same frequency. By increasing the number of available relays, resource sharing can lower the probability that all the useful relays are busy when the AR packet is sent.

3.3.2 Protocols based on global parameters

In the *GAB* protocol, allocation is computed by the APs. Similarly to the *LAB* protocol, a user which joins the network first broadcast a AR packet. The relay(s) which decode this packet immediately forwards it to the AP, which computes the best allocation for all the users based on the location of the newcomer. This information is included in the AS packet, which is sent back by the AP, and broadcast also by the relays. Differently from the case of cellular-like network, it is possible that the AR packet forwarded by the relay(s) is not received at the AP since it is already busy with another communication. This may result in longer allocation times. In order to reduce this delay, the AP keeps listening over the uplink channels even when it is receiving another transmission. In this way, it can update its information about the network topology, and broadcast it as soon as the ongoing transmissions is concluded. Alternatively, periodic broadcast of AS packets can be performed, at the cost of possible unnecessary transmissions, depending on the users mobility.

An example of how the protocol works is depicted in Figure 3.15.

If relays are shared, they forward the AR packets on both the frequencies, and wait for the answer of one or both the APs. Since transmissions are uncoordinated, in this scenario the probability that the information owned about the network topology by the two APs are different is much higher. This is why it is preferable that the relays always forward also the AS packets, which can be then received by the other

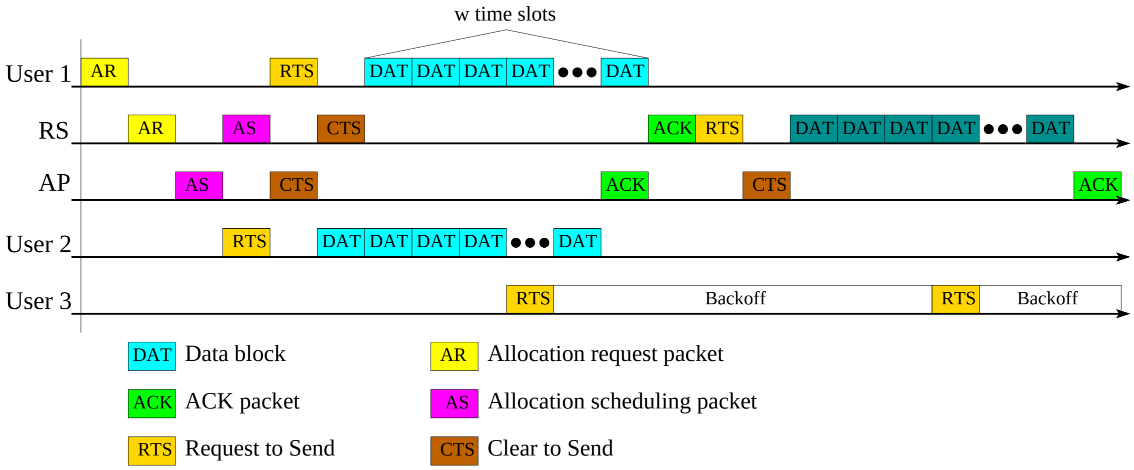

Figure 3.15: Time slot scheduling for the *GAB* protocol in an ad hoc scenario. User 1 first transmits an AR packet to find out its route to the AP; the AR packet is forwarded by the relay to the AP, which replies with the AS packet, relayed back to user 1. Now, a RTS is sent by user 1 to probe the relay availability, confirmed by a CTS. The data transmission then takes place, followed by an ACK. The RTS–CTS handshake is also required between the relay and the AP. User 2 is instead already allocated to the AP, and can transmit after the RTS–CTS packets exchange. Finally, user 3 tries to contact the AP, which is however involved in another transmission, and cannot reply with the CTS. User 3 is then forced to enter backoff.

AP, and used to keep the network topology information updated.

Finally, we remark that opportunistic routing cannot be used efficiently here, due to the fact that transmissions are not aligned. If the network is loaded, it is unlikely that surrounding relays, apart from the intended destination of a user transmission, are able to listen to the whole transmission and help as forwarders. Therefore, we do not apply this option in this specific scenario.

3.3.3 FDMA network

FDMA can be used also in this scenario, so as to avoid interference between simultaneous transmissions. However, we observe that, due to the presence of the RTS/CTS handshaking, the number of concurrent transmissions is much lower than in the cellular-like scenario, thus limiting the need for an orthogonal separation of the users. On the flip side, however, since a single transmission at a time can be received by a relay, the load balancing between the relays plays a key role, being responsible for the queue length and, in the end, for the average delivery delay of the packets.

3.3.4 Simulation results and comparison

In ad hoc networks, most of the elements which characterize the cellular-like networks are not present. The absence of a global coordination makes it difficult to

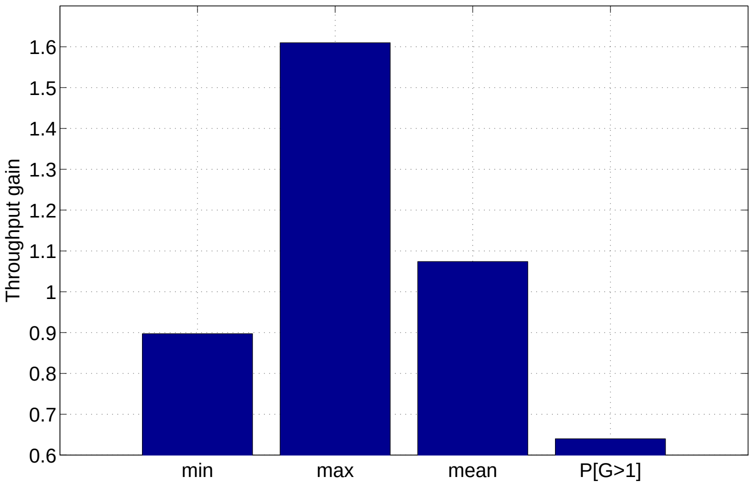

Figure 3.16: Throughput gain in a CDMA-based ad hoc scenario, without SIC. Allocation is done via the *GAB* protocol, implementing the *GEO* allocation algorithm.

perform some of the operations which grant the highest benefits in terms of throughput, like packet superposition and opportunistic routing. This is true also when the relays are shared, since superposition of packets intended for two different APs is not possible. As a consequence, the gain due to relay sharing appears to be much lower. In addition, control packets are more likely to be lost, since surrounding relays may not be able to listen or forward them, being involved in other communications. The resulting user allocation is therefore suboptimal, and, when infrastructure sharing is enabled, the coordination between the two APs is hardly maintained.

The simulations confirm this idea. We focused on the *GEO* algorithm, since usually interference here is much lower than in the cellular like network. In fact, every relay/AP can receive one transmission at a time. Correspondingly, the overall throughput is much lower, as is the network capacity. We investigated a scenario with $k = 3$ relays per network and $N = 12$ users per network. We first analyzed the CDMA case, with and without SIC, and then we compared it with the FDMA case.

For the CDMA case, the first observation is that the effectiveness of relay sharing strongly depends on the specific topology. In fact, although a maximum gain of 61% was achieved, relay sharing was beneficial only in the 64% of the topologies, with an average gain of 7% (Figure 3.16).

When SIC is employed [13], although the absolute throughput is much higher (62% higher) the margin for further improvement, offered by relay sharing, is even lower, and in most of cases a throughput loss is instead obtained. This is due to the fact that now the burden of an overloaded relay cannot be sustained by a strong backhaul link: on the one side, the relay can receive one transmission at a time, thus highly increasing the expected time for a user to use its access link; on the flip side, also the AP can receive only one transmission at a time, from either a user or a relay, resulting in the classical sink bottleneck observed also in sensor networks.

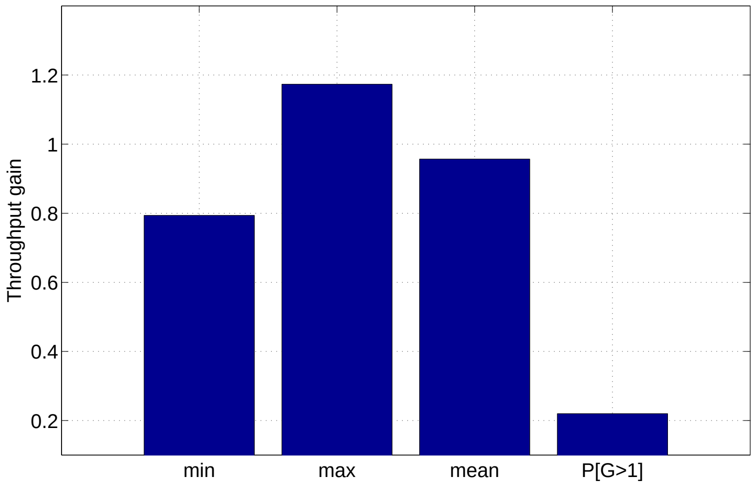

Figure 3.17: Throughput gain in a CDMA-based ad hoc scenario, with SIC. Allocation is done via the *GAB* protocol, implementing the *GEO* allocation algorithm.

Since FIFO policy is adopted at the relays, the high traffic towards the destination AP of the first packet in the relay queue can stop also the traffic meant for the other AP, if relay sharing is enabled. As Figure 3.17 clearly shows, there is a gain only in the 22% of the cases, although the throughput loss is mostly negligible. In some specific topologies, anyway, relay sharing can still offer a slight performance improvement, up to 17%.

Finally, we put our attention to the FDMA scenario. The absence of interference grants an overall higher aggregated throughput (16% higher than in the CDMA+SIC case), which can lower the transmission time and hence partially reduce the time needed to use the access link for relayed users. Relay sharing can increase this benefit, by granting a lower expected distance from the closest relay. In fact, although a throughput improvement is registered only in the 62% of the cases, the average throughput gain is 4%, with a peak gain of 33%, as depicted in Figure 3.18.

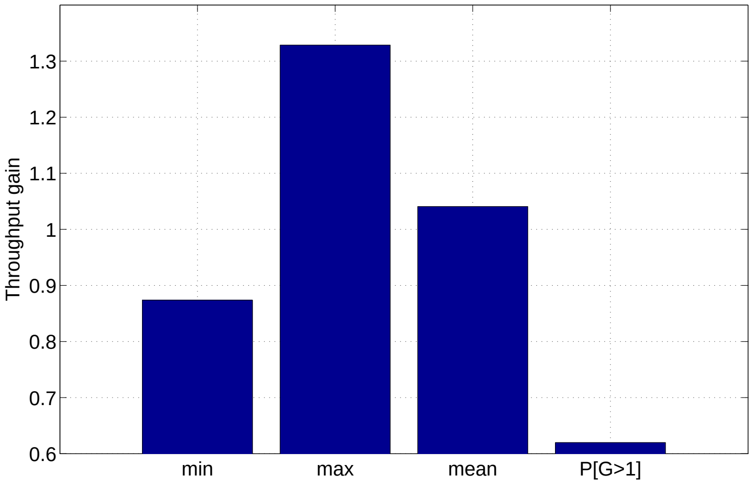

Figure 3.18: Throughput gain in a FDMA-based ad hoc scenario. Allocation is done via the *GAB* protocol, implementing the *GEO* allocation algorithm.

Table 3.1: System Parameters.

Topology	
Relays per network k	3
UEs per network $N_1 = N_2$	20
Side of BS deploying area s	20 m
Maximum deployment distance d_h	75 m
Relay distance factor μ	2/3
Physical Layer	
UE tx power P_t	0.25 W
Max equivalent relay tx power P_R	2 W
Relay power allocation factor η	2
Processing gain N_s	32
Path loss exponent α	3
Path loss factor A	1000
Shadowing standard deviation σ	8 dB
Noise power N_0	-103 dBm
Coverage angle $\hat{\delta}$	$\pi/2$
Attenuation factor Λ_α	0.1
Attenuation factor Λ_β	0
Attenuation factor Λ_γ	0
Multiple Access technique	CDMA, FDMA
Modulation	BPSK
Successive Interference Cancellation	on, off
Medium Access Control (MAC) layer	
Number of blocks per packet w	6
Block length b	512 bits
DATA–ACK sequences per cycle k_r	2
Buffer length q	16 pkts
Maximum number of superimposed packets M_{pkt}	6
AS packets relay forwarding	on
UE allocation	local, global
Opportunistic Routing	on, off
Allocation scheme	GEO, CBA, TBA

4 Conclusions

In this deliverable, we evaluated the theoretical capacity gain that can be granted by uplink spectrum and relay sharing, which appears to be significant. Moreover, we investigated algorithms (meant as theoretical approaches) and protocols (i.e., practical strategies) to realistically approach this gain in real networks. We implemented four algorithms and three protocols, and validated them in different scenarios.

Clearly, there are several combinations that can still be thought of, yet we believe the results presented here are covering the entire span of the possibilities and give clear indications that the advantage of relay sharing may be consistent (around 20% of capacity) in several scenarios. We remark that this gain comes from a pure networking perspective [3], i.e., there may be other aspects from the underlying layers that still improve the gain. In particular, the usage of more refined PHY layer techniques [13, 7] may lead to a further performance improvement, and modifications based on cross–layer approaches [10, 2] can also be added to the protocols.

As further steps, these findings can be merged within system level simulation approaches envisioned by the SAPHYRE project [1]. A comprehensive system evaluation at a global level, also possibly including results from practical testbeds, is surely an interesting validation of these points.

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