

# WIRELESS PEER-TO-PEER COOPERATION: WHEN IS IT WORTH ADOPTING THIS PARADIGM?

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## ABSTRACT

Cooperation over short-range wireless links among devices downloading remote contents through cellular links is a paradigm quickly gaining ground in the view of answering some of the main issues next-generation wireless applications will rise. Among others, energy consumption, data rate, and transfer time are parameters that may likely benefit from this novel communication concept. Aim of this paper is to contribute to a better understanding of which are the wireless hybrid scenarios where cooperation actually works and which combination of wireless links is more performing with respect to others. Our analysis focuses on different short-range networks technologies for a peer-to-peer communication among cooperating entities, such as Bluetooth, 802.11g, and ad-hoc 802.11g. Long range (cellular) links we concentrate on are EDGE, UMTS and HSDPA.

## I. INTRODUCTION

In recent years, cooperation in wireless environments has attracted the interest from both research and industry communities. With the advent of novel multimedia interactive services and high performing applications, the need for considerable improvements, both at the system and at the device level, clearly arises. By focusing on services, such as, for instance, TV-on-mobile and video streaming, the increasing difficulty in delivering services at an acceptably good Quality of Service is manifest. Cooperation, involving almost all layers of the ISO/OSI model, is a promising feature that offers a viable solution to aforementioned issues. A comprehensive survey on cooperation in communication systems is given in [1] and in [2], where cooperation issues at the Physical, Medium Access Control, and Network layers are addressed. A cooperative architecture paradigm is introduced in [1] and in [3], based on a peer-to-peer wireless communication paradigm where some devices exchange data contents over short-range links, while a cellular link is used as a service entry point, see Figure 1. In so doing, the involved entities reduce the costs (in terms of both money and energy) afforded for the cellular link by sharing their CPUs and their batteries to achieve the common goal of downloading a web content. In [3] we have analyzed advantages and drawbacks of a cooperation among users accessing a cellular network (GPRS) and exchanging data over short-range Bluetooth links. It has been demonstrated that complementarities and capabilities of cellular and short-range radio networks concur to offer significant advantages to cellular subscribers (up to 44.3% energy saving and a doubled data rate in a scenario involving two cooperating devices); this being the main motivation for conducting further investigations.

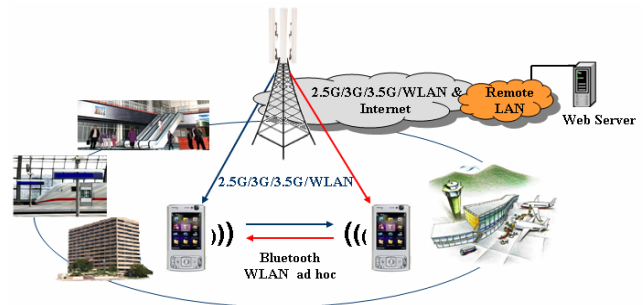


Figure 1: Wireless cooperative scenario.

In the present paper, we take our research forward by analyzing the opportunity of cooperating also when systems different from GPRS and Bluetooth are involved, in the view of future dynamic and multi-technology scenarios. We consider different combinations of cellular and short-range links and try to conduct a comprehensive analysis of their relevant pros and cons. Attention is on solutions where *Bluetooth*, *WLAN (802.11g)*, and *ad-hoc 802.11g* play the role of cooperative channel, while *EDGE*, *UMTS*, and *HSDPA* provide the cellular links. Cooperation in a WLAN-Bluetooth scenario has also been thoroughly analysed.

Motivations for this study are manifold: (i) addressing the study of novel scenarios will push forward the overall knowledge of the actual potentialities of wireless cooperation; (ii) to the best of our knowledge, no contributions is available from the literature comparing the performance of different short-range links implementing cooperative behaviours; (iii) a thorough analysis of different scenarios will support user decisions and behaviour during cooperative sessions.

## II. THE DEPLOYED TEST-BED

In order to conduct a comprehensive performance evaluation campaign of the envisaged *cooperation architecture*, a suitable test-bed is deployed. It foresees the presence of a remote server, where mobile terminals can download a mp4 file from, and the use of commercial mobile phones (Nokia N95), into which an ad-hoc mobile application is implemented (an enhanced version of the one used for early studies in [3]). As concerns the short-range communication, Bluetooth, WLAN, and ad-hoc connection set-up capabilities are integrated into the application. The server delivers a complete file to the non cooperating clients, while partial files are delivered to cooperating clients. To this aim, a HTTP transaction management functionality is implemented, working over the cellular links. The 1.1 version of HTTP protocol is exploited to match the re-

quirement of a cooperative *dynamic* scenario, as the HTTP/1.1 *Range Request* [4] header is intended to support dynamic data delivery. The test scenario we consider for our studies foresees two sample users interested in downloading the same data file (a 2600 KBytes mp4 file) from a web server. The two terminals download different shares of the same video sequence by accessing the server through either an EDGE, or a UMTS, or a HSDPA link; at the same time, by means of a short-link connection (either Bluetooth, or WLAN, or ad-hoc), they exchange the relevant portions of data in a cooperative fashion. The use of the Nokia energy profiler tool, pre-installed into each mobile device, allows to gather very precise energy consumption measurements. Clearly, the described scenario is a simplified representation of a real architecture, in which, reasonably, more than two terminals will cooperate. Notwithstanding, it is an effective test-bed for experimental measurements aiming at assessing the benefits/drawback introduced by the cooperative behaviour of multimodal terminals.

### III. PERFORMANCES AND RESULTS

In this section we will go into the details of our comparative analysis involving the different combinations of long range and short range technologies. The performed campaign is conducted as follows. A first set of measurement tests considers mobile phones downloading a video file from a remote server by using conventional cellular communication systems in a stand-alone fashion. Subsequently, under the same conditions, further tests are conducted when the cooperation over short-links is enabled. The results shown in the present paper depict the gain achieved through cooperation obtained by comparing the output of the two set of tests. In the remaining subsections we will report the main results in terms of energetic and data rate gains for different study cases. Before going on, it is worth highlighting that a general assumption is usually made in the literature when dealing of such a kind of cooperation paradigm: a successful outcome of the cooperation is conditioned by the expression in (1), where  $R_{SR}$  is the data rate of the short-range link and  $R_C$  is the data rate over the cellular link.

$$R_{SR} > R_C \quad (1)$$

The interesting point which derives from the output of our study is that, as it will become clearer in the remaining part of the paper, it has been observed that the condition above refer to the achievement of the maximum available energetic and data rate gain, while still, sometimes, a gain is achieved when  $R_{SR}$  falls below the value of  $R_C$ . As we will show, if condition (1) is not met, then both data rate and energetic gains will experience a manifest lessening but for some of the considered configurations are still present. The limit condition for having a minimum data rate/energetic benefit in some configuration thus becomes:  $R_{SR} > \frac{1}{2} \cdot R_C$ .

#### A. Bluetooth Radio Interface

Our cooperative communication paradigm is tested under symmetric data transmission conditions. For this case, the standard Bluetooth v2.0 [5] declares a value of 434 Kbps for DH5 packet

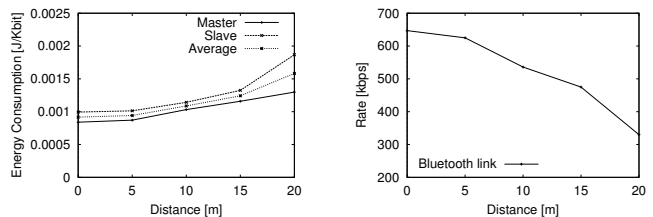


Figure 2: Bluetooth energy and data rate vs the distance.

type, 870 Kbps for 2-DH5 packet type, and 1307 Kbps for 3-DH5 packet type. Nevertheless, these values do not take into consideration the distance between devices. In our analysis, we want to investigate the effects of this parameter as well. Hence, in Figure 2 we report our test results, performed at different distances (0-20m range), where the data rate and the energy consumption related results are plotted for a symmetric Bluetooth communication session without cooperation. The reader notices how the data rate decreases with the distance, while the energy per Kbit increases with the distance between the peer entities (by exhibiting different behaviours for master and slave of the Bluetooth link). Noteworthy, at a distance of 20 m, the Bluetooth symmetric data rate value falls below 330 Kbps. This value, compared to the UMTS theoretical value of 384 Kbps, does not meet condition (1); thus negatively affecting data rate and energetic gains, as it will become clear later in this section. Logically, the decreasing trend in the performance of the cooperation through short-range Bluetooth when varying the inter-device distance is steeper if a faster cellular link is used (such as for example HSDPA).

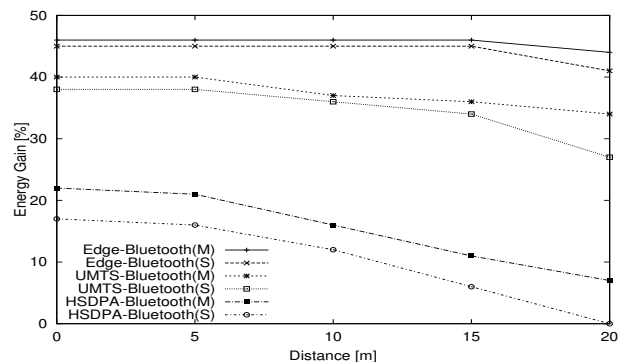


Figure 3: Energetic gain in Bluetooth cooperative scenarios.

#### 1) Energy Consumption and Data Rate Results

In Figure 3 the energy consumption gain is plotted, compared to the non-cooperative case, when Bluetooth is used in cooperation with EDGE, UMTS, and HSPDA cellular links respectively. It is worth pointing out that results are strongly related to both the inter-device distance and the role played by the device (master/slave) in the communication session. When EDGE is used to establish a cellular link, the gain ranges between a minimum value of 41%, for a slave and 20 m inter-device distance, and a value of 46%, for a master and 0 m inter-device distance.

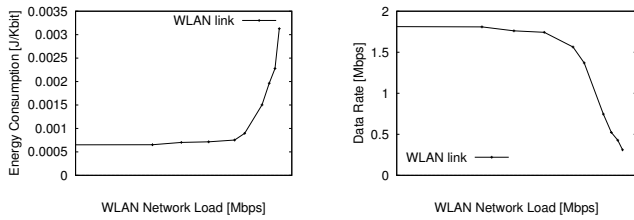


Figure 4: WLAN energy and data rate vs network traffic load.

When UMTS is used, the range of energy consumption gain widens from the minimum value of 27% (slave, 20 m between devices and condition (1) not met) to a maximum value of 40% (master, 0 m between the devices). When HSDPA is used, instead, the energy consumption gain is strongly lessened, because the scenario is far from meeting condition (1). In fact, at low distances between devices we still have some gain (about 20% at 0-5 m between the devices); differently, by increasing the distance the gain decreases and reaches the 0 gain point at the maximum distance between the devices (20 m). For a detailed overview of the results, please refer to Tables 1 and 2.

The results of the data rate analysis are straightforward. When considering any cooperative scenario that respects relation (1), the data rate is almost doubled compared to the non-cooperative case. This is what we expected, as the two cooperating devices accumulate the cellular links. In all the other cases this is not true. For instance, in all the HSDPA-Bluetooth scenarios the impossibility of meeting condition (1) makes the data rate gain strongly decrease. The Bluetooth link becomes the bottleneck of the communication paradigm and when the devices are about 10m (or higher) distant with respect one another it is not worth anymore cooperating at all, whereas the data rate gain decreases to a 0% value.

## 2) The WLAN-Bluetooth Scenario

A particular attention shall be paid to this specific scenario. In fact, when considering WLAN (802.11g) as the main service entry channel and Bluetooth as the short range link, the relation (1) is not met. This adversely affects data rate and energetic gains. In standard conditions, Bluetooth data rate cannot compete with WLAN. Notwithstanding, we analyze also the effect that an increase in the number of transmitting WLAN terminals, with the consequent reduction of the overall WLAN capacity, may have. This phenomenon, in fact, may bring the rate available to each WLAN user down to values comparable with the typical Bluetooth transmission rates. In this conditions the users will likely gain advantages from cooperation and their willingness to cooperate increases. A Bluetooth based cooperation among users in the WLAN will, at the same time, reduce the data transmission rate on the WLAN links of each cooperating user, this increasing the WLAN capacity in terms of number of users which contemporary access the covered wireless hot-spot. This phenomenon is substantiated by the experimental results shown in Figure 4. The energy consumption per Kbit of data and the data rate (Kbps) are plotted for two cellular phones downloading the required data from the IEEE 802.11g

Table 1: Energy values and gains in the cooperative scenarios.

Cellular	Short-range	Distance	J/Kbit	Energy gain
EDGE	Bluetooth (M)	0-15 m	0.0056	46%
EDGE	Bluetooth (S)	0-15 m	0.0057	45%
EDGE	Bluetooth (M)	20 m	0.0058	44%
EDGE	Bluetooth (S)	20 m	0.0061	41%
UMTS	Bluetooth (M)	0-5 m	0.0025	40%
UMTS	Bluetooth (S)	0-5 m	0.0026	38%
UMTS	Bluetooth (M)	10 m	0.0025	37%
UMTS	Bluetooth (S)	10 m	0.0027	36%
UMTS	Bluetooth (M)	15 m	0.0026	36%
UMTS	Bluetooth (S)	15 m	0.0027	34%
UMTS	Bluetooth (M)	20 m	0.0027	34%
UMTS	Bluetooth (S)	20 m	0.0030	27%
HSDPA	Bluetooth (M)	0 m	0.00117	22%
HSDPA	Bluetooth (S)	0 m	0.00125	17%
HSDPA	Bluetooth (M)	5 m	0.00118	21%
HSDPA	Bluetooth (S)	5 m	0.00126	16%
HSDPA	Bluetooth (M)	10 m	0.00127	16%
HSDPA	Bluetooth (S)	10 m	0.00132	12%
HSDPA	Bluetooth (M)	15 m	0.00133	11%
HSDPA	Bluetooth (S)	15 m	0.00143	6%
HSDPA	Bluetooth (M)	20 m	0.0014	7%
HSDPA	Bluetooth (S)	20 m	0.00168	none
EDGE	WLAN	0-20 m	0.0061	41%
EDGE	ad-hoc	0-20 m	0.006	42%
UMTS	WLAN	0-20 m	0.0029	28%
UMTS	ad-hoc	0-20 m	0.0029	29%
HSDPA	WLAN	0-20 m	0.0018	none
HSDPA	ad-hoc	0-20 m	0.0017	none
WLAN	Bluetooth	0 m	0.0013	none

WLAN Access Point. In this phase, the terminals do not cooperate with one another. Curves are sketched by varying the WLAN background traffic load (generated through the open-source MGEN tool). It clearly appears that, by increasing the overall traffic load, both the energy consumption increases and the data rate of each cellular phone decreases. For overall traffic load values higher than 18,5 Mbps, observed cellular phones are not able anymore to access the WLAN network. Merging this figure with Figure 2 we notice that now there are some ranges of parameters values in which maybe it is worth letting the two terminals cooperate through their Bluetooth interfaces while downloading data from the WLAN Access Point. For a distance between terminals of about 5 m or less and an overall WLAN traffic load higher than about 18 Mbps, we observe advantageous conditions to the cooperating users in terms of both achievable data rate and energy consumption.

A further step in our analysis foresees the investigation on a key factor, the Bluetooth and IEEE 802.11g mutual interference in the 2.4 GHz-ISM-Band. The suspect is that the coexistence of the two interfering systems will further reduce cooperation applicability range. Our worries are confirmed by the outputs of our test campaigns conducted under different WLAN traffic loading levels (by fixing at 1 m the distance between the

Table 2: Data rate values and gains in the cooperative scenarios.

Cellular	Short-range	Distance	Data rate	Rate gain
EDGE	Bluetooth	0-20 m	296 Kbps	97%
UMTS	Bluetooth	0-20 m	686 Kbps	99%
HSDPA	Bluetooth	0 m	1290 Kbps	12%
HSDPA	Bluetooth	5 m	1246 Kbps	8%
HSDPA	Bluetooth	10 m	1070 Kbps	none
HSDPA	Bluetooth	15 m	946 Kbps	none
HSDPA	Bluetooth	20 m	656 Kbps	none
EDGE	WLAN	0-20 m	296 Kbps	97%
EDGE	ad-hoc	0-20 m	296 Kbps	97%
UMTS	WLAN	0-20 m	682 Kbps	98%
UMTS	ad-hoc	0-20 m	682 Kbps	98%
HSDPA	WLAN	0-10 m	1382 Kbps	20%
HSDPA	WLAN	10-20 m	1356 Kbps	18%
HSDPA	ad-hoc	0-10 m	1440 Kbps	25%
HSDPA	ad-hoc	10-20 m	1418 Kbps	23%
WLAN	Bluetooth	0 m	692	none

cooperating cellular phones) to study the impact of Bluetooth interference on the WLAN achievable rate. As expected, compared to the case of WLAN transmission only, the downloading rate each user experiences over the WLAN link is reduced; this making Bluetooth cooperation not beneficial anymore.

Based on the obtained results, we can state that even when operating within the theoretical applicability ranges for WLAN-Bluetooth cooperation, the mutual interference of the considered radios seems to exclude any real advantage. Nevertheless, extensive research has been conducted dealing with 802.11 and Bluetooth coexistence and mutual interference; as a result, many possible solutions have been proposed (Adaptive Frequency Hopping, Adaptive Packet Selection, Adaptive Packet Scheduling, Alternating Wireless Medium Access, Packet Traffic Arbitration), the reader can refer to [6], [7] and [8] to find more details on this matter. Proposed solutions could be a viable add-on to the implemented cooperative WLAN-Bluetooth scenario. This gives us the opportunity to affirm that still a deeper analysis needs to be performed before a-priori excluding the WLAN-Bluetooth cooperative scenario from the set of feasible network combinations.

### B. 802.11g Radio Interface

It is worth recalling that the infrastructure-based nature of the network makes cooperation depend on the existence of a network and on the accessibility of its Access Point (AP). In this case, cooperating devices exchange information (downloaded from cellular links) through the Access Point. The latter could be a limitation in specific cases. We tested the accessibility to the 802.11g AP under different traffic loading conditions and observed that cooperation was not possible for traffic loads higher than 18 Mbit/s, since in these conditions mobile phones will not be able to access the network. This is caused by the lack of suitable admission control policies. Similar to the Bluetooth link case, we made some measurements campaigns to highlight the performance of a 802.11g short-range link be-

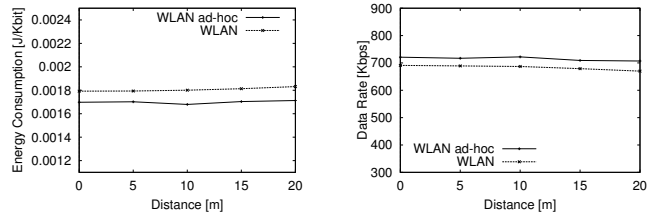


Figure 5: Energy consumption and data rate vs the distance for WLAN infrastructured and ad-hoc networks.

tween two devices, in terms of data rate and energy consumption, by varying the distance from the Access Point. For a better comparison with the Bluetooth case, we took into consideration only the 0-20 m range of distances. As plotted in Figure 5, there is not a very relevant variation of the data rate and the energy consumption in the considered range of distances.

### 1) Energy Consumption and Data Rate Results

As there is not a very relevant energetic and data rate variation with the distance from the AP over the WLAN link, we will consider an average value for all the considered measurements. By exploiting WLAN as a short-range link in combination with EDGE an energy consumption gain of about 41% is achieved, in combination with UMTS a gain of 28% is obtained and in combination with HSDPA no energetic gain is achieved, see Figure 6. Concerning the data rate results, exploiting a WLAN network for a cooperative link offers a data rate gain of about 100% in both scenarios where EDGE and UMTS cellular links are used and of about 19% with HSDPA. For more details please refer to Tables 1 and 2.

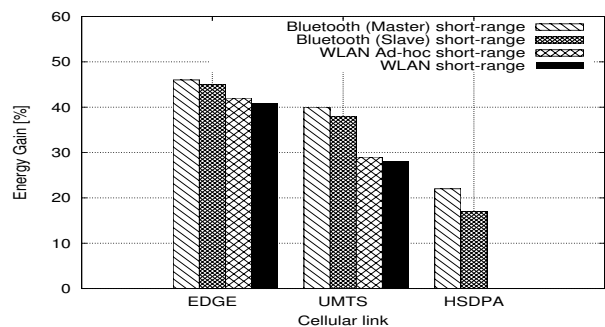


Figure 6: Energetic gain in scenarios at 0 m distance.

### C. 802.11g ad-hoc Short-Range Link

It is worth recalling the decentralized nature of this kind of solution, which is an appealing characteristic in the view of a cooperative architecture. In fact, in case of ad-hoc configuration, the cooperating devices can directly exchange information without passing through the AP (and likely be charged a cost). Similar to the other considered short link solutions, energetic and data rate measurements have been performed for a 802.11g ad-hoc link, in the range of 0-20 m distance between the involved devices. Like in the WLAN case, the two parameters do not have relevant variations in the considered range.

When comparing the ad-hoc and the WLAN link (see Figure 5) the ad-hoc link is always the best performing choice.

#### 1) Energy Consumption and Data Rate Results

Like in the WLAN case, we will consider an average value in all the considered measurements in the 0-20 m range. Results relevant to 802.11g ad-hoc technology in combination with EDGE, UMTS, and HSDPA cellular links are available from Figure 6. An energy consumption gain of about 42% at all distances can be noticed when in the presence of an EDGE cellular link; a gain of 29% is obtained with 802.11g ad-hoc in combination with UMTS; no energetic gain is achievable in cooperation with HSDPA. Exploiting an ad-hoc solution for a cooperative link offers a data rate gain of about 100% in both scenarios where EDGE and UMTS are the cellular link, and a gain of 24% with HSDPA, see Tables 1 and 2.

#### D. Comparisons, Pros and Cons

Based on observed results, in this section we will formulate overall considerations on the cooperative use of short-range wireless links, while trying to understand which cooperative scenarios perform better than others.

From the "data rate gain in cooperation" point of view, we can affirm that the ad-hoc short-range is always the best performing technology with a little advantage on the 802.11g infrastructured link. This is true for network loading below the congestion level. When EDGE and UMTS are used as the cellular link, a doubled data rate is observed, which is not always true for the case of a short-range Bluetooth link. In fact, when a UMTS cellular link is used, the data rate gain with the adoption of Bluetooth has a lessening at a distance of 20 m between devices. When HSDPA is the cellular link, the 802.11g technology is still over-performing Bluetooth, for which the negative influence of the inter-device distance plays a very big role. Similar considerations can be made for the transfer time results which are inversely proportional to the data rate results.

Considerations about energy consumption gains are more problematical. By comparing WLAN and ad-hoc scenarios, we immediately notice that WLAN ad-hoc is more energy efficient. In both EDGE and UMTS long-range link cases, the energy consumption gain over the short-range ad-hoc link is higher than the one obtainable by means of WLAN links. By considering the Bluetooth short-link, we can affirm that, in general, it is better performing than WLAN and ad-hoc links, because it offers higher energy consumption gains and it offers also energetic gains in collaboration with HSDPA; but the distance between devices is a key parameter to monitor for this kind of solution. A drawback of the Bluetooth technology, besides the cited short coverage range, is represented by its manifest limitations when the cooperative scenario involves more than two terminals. A Bluetooth Piconet is limited to 8 devices (1 master and 7 slaves) and no direct communication is possible between slaves. These issues are not applicable to either WLAN and ad-hoc technology.

Based on the considerations above, we can state that there is no cooperative scenario which is always outperforming the other ones and, thus, is always to be considered as the best

scenario is possible. Differently, parameters such as battery power level, urgency of the file to download, distance between the devices, and, likely, other subjective parameters, need to be jointly considered in each situation and condition to select the most advantageous cooperative scenario.

Clearly, with the evolution in the short range networks and the imminent advent of ultrawide-band (UWB) Bluetooth, things will definitely improve. With the important energetic and data rate (up to 200 Mbps) enhancements, UWB Bluetooth will surely have an important role in the cooperation paradigm.

## IV. CONCLUSIONS

In this paper we introduced novel significant results testifying to the high potential of cooperation in hybrid wireless network scenarios. Specifically, the focus of the present paper has been on the analysis of different short-range technologies to be deployed as a means for cooperative data exchanges. Our contribution compared the performance of solutions involving EDGE, UMTS and HSDPA, long-range cellular link providers, and Bluetooth, 802.11g and 802.11g ad-hoc, as short-range wireless link providers. The distance between devices has also been considered as a test parameter and it revealed to be particularly relevant for Bluetooth links, which showed to be less performing when the distance between the cooperating units becomes greater. This is not the case of WLAN networks. Based on the obtained results, parameters such as battery power level, urgency of the file to download, distance between the devices, need to be considered in making the choice of the best cooperative scenario. In the future, we intend to focus our analysis of scenarios with an increased number of devices and on an enhanced aggregation algorithm, adapting to the mismatched bandwidth of the links and not simply splitting on a fifty-fifty basis the amount of data to download. Studies already started but we are not able to give comprehensive results yet.

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