Energy-Efficient Cooperative Techniques for Multimedia Services over Future Wireless Networks

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***Abstract*—In this paper we develop and analyze energy-efficient cooperative techniques for multimedia streaming applications in wireless networks. The concept of combined cellular-SR network architecture is coupled here with different video coding schemes for the goal of achieving robust transmission over wireless channels and energy saving. The strategies are analyzed in different technology settings, showing promising power saving potentials in comparison to the state-of-the-art non-cooperative operation.**

I. INTRODUCTION

Video streaming over IP-networks has become increasingly popular during the last years. Internet video and web-based multimedia applications are currently required as standard features from the users community. In the wireless domain, the quick development of new communication techniques as well as advanced terminal capabilities has determined a big potential of video over wireless (*e.g.*, TV-on-mobile). However the strict constraints of real-time video streaming in terms of bandwidth, delay, and packet loss involve several challenges for the transmission over error-prone wireless fading channels. Existing communication protocols are not specifically designed to support video requirements. Therefore different video coding schemes have been introduced, such as Multiple Description Coding (MDC) and Scalable Video Coding (SVC). Both schemes provide an effective and flexible solution to achieve robust transmission over wireless channels.

Furthermore, a major challenge for video applications over wireless networks is the power consumption of mobile handhelds, as the devices are battery driven. Progress in the technology and enhanced applications are not adequately supported by advances in battery capabilities. In addition, the screen size as well as the resolution of the terminals for video applications is increasing, involving even higher energy consumption. A possible solution which has been proposed to cope with the energy problem is cooperation among wireless terminals. The main idea is to exploit the combination between the cellular (C) and short-range (SR) network platforms [1], as illustrated in Figure 1. Several works of research have shown the promising potentials of this approach (see, for instance, [2]). In this paper we aim to combine the flexibility and robustness of video coding techniques with the high power saving potentials of cooperative strategies. Therefore we explore and analyze several scenarios with the goal of achieving seamless quality of service and power saving gain for multimedia applications over wireless networks.

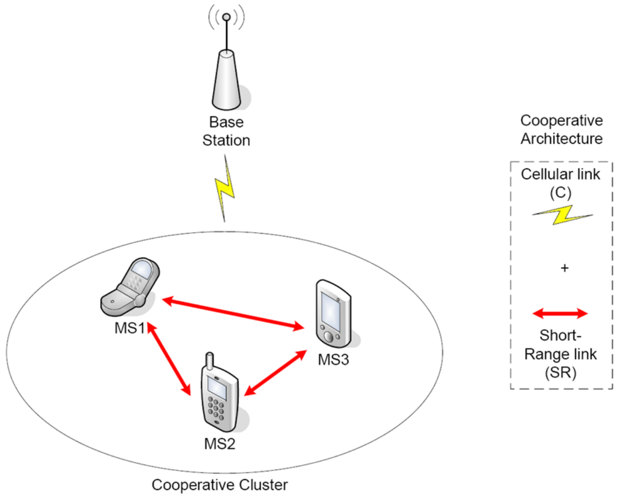

Fig. 1. Cooperative hybrid network architecture.

II. ENERGY-EFFICIENT COOPERATIVE TECHNIQUES WITH DIFFERENT VIDEO CODING SCHEMES

In this section, several cooperative strategies for video streaming applications are presented and discussed, by using MDC and SVC.

A. MDC Technique

Multiple Description Coding (MDC, [3]) is a video coding scheme where the data stream is split into a set of multiple substreams (descriptors) that can be decoded independently. The video quality at the receiver is proportional to the number of correctly received descriptors. The cost of MDC is a certain amount of redundancy between descriptors. The property of independence between different descriptors makes this technique particularly suitable for the application of cooperative principles. We rely on the hybrid network architecture given in Figure 1. Our analysis is based on the following assumptions:

- a number of wireless terminals, interested in the same service, are distributed under the coverage of a central

access point (AP). The AP provides a multicast transmission service and transmits according to the principle of Time Division Multiple Access (TDMA);
- all terminals support two air interfaces: one to the cellular link (C) for the AP reception, and one to the SR link for exchanging packets locally.

The service is split into substreams according to the MDC principles. We focus on a given number J of terminals that are located in close proximity and form a *cooperative cluster*. We also assume, for simplicity and without loss of generality, that the number of transmitted substreams is also set to J. In order to get the best service quality, each user has to receive all the J substreams. At this point we distinguish two possible operation modes. In the non-cooperative case (self-sustaining or autarky), the terminals do not cooperate and receive all the J substreams with autonomous operation over the downlink channel.

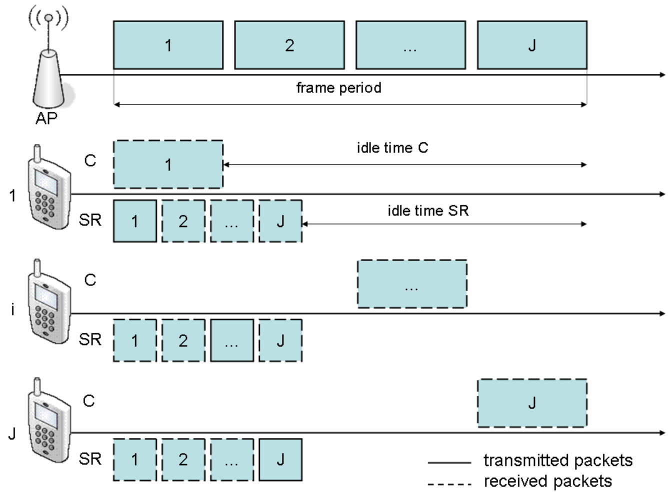

Fig. 2. Principle of cooperative reception of J MDC substreams.

On the other hand, in the cooperative case, each unit receives only one out of the J substreams and forward it to the other *J-1* cooperative terminals over the SR communication link, as illustrated in Figure 2. As we will show, in this latter scenario the power consumption of wireless terminals could be dramatically reduced by switching the receiving devices to *low-power* mode during idle periods. Furthermore, the communication over the SR link is more efficient, as the *energy/bit* required for the transmission by current technology is lower.

B. SVC Techniques

Scalable Video Coding (SVC, [4]) is analogous to MDC. In this coding scheme, the video signal is split into a base layer (BL) and several enhancement layers (EL). The BL provides coarse video quality, while the EL can be used progressively to refine the achieved quality, thus providing scalability. The main difference with MDC is the introduction of a hierarchical structure between the substreams. A more detailed comparison between the two schemes can be found in [5]. In SVC the reception of the BL is crucial, therefore it must be protected against transmission errors by channel coding. SVC has been recently standardized as an extension of the H.264/AVC [6]. In the same assumptions given for the MDC framework, here we aim to explore the cooperative power saving potentials of SVC for video services over wireless networks. The following strategies are developed in order to provide seamless quality of service and achieve energy saving.

1) Base Layer Reception Diversity (BL-RD): A first idea, illustrated in Figure 3, is similar to the MDC technique. We focus on a number of J terminals, equal to the number of SVC enhancement layers (leading to $J + 1$ overall number of substreams). As the BL is crucial in SVC, in this scheme we assume that $N \leq J$ terminals receive the BL and forward it to the SR link. On the other hand, the EL are received separately and forwarded by all J cooperating terminals, in the same way described for MDC. In this way the BL is protected against transmission errors by diversity. In comparison to the scheme of Figure 2, this comes at the cost of a certain amount of redundancy due to the additional reception/transmission of the BL. However, advantages of SVC are higher coding efficiency, large applicability due to standardization [6], and high flexibility which can be provided towards a variety of heterogenous terminals.

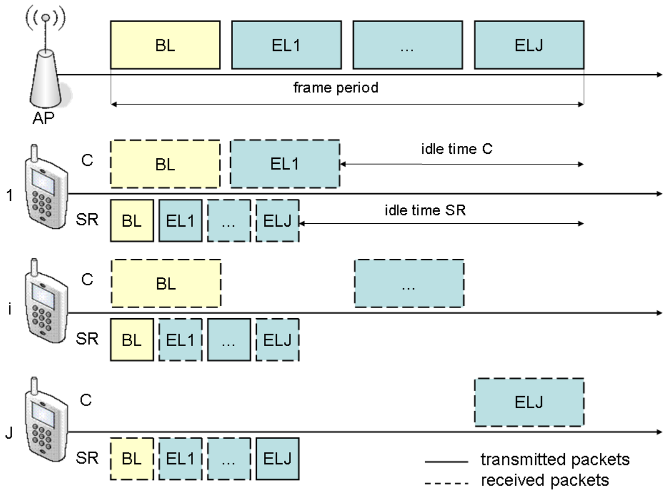

Fig. 3. Principle of cooperative reception of SVC substreams with one base layer and J enhancement layers, BL reception diversity.

In the proposed cooperative framework the BL reception is ensured by diversity, leading to a possible relaxation of the transmission overhead required by FEC (Forward Error Correction) techniques. Moreover, ARQ (Automatic Retransmission Request) through a feedback channel could be avoided. As it will be shown, the major advantage of the technique is energy saving, very promising for upcoming video and multimedia applications on portable devices.

2) Dynamic Cellular Channel Allocation (DCA): In this second strategy, shown in Figure 4, we assume that CSI

(Channel State Information) about the wireless channel is available at the transmitter (a feedback channel is available). At any moment, the AP estimates the best channel C_i and transmits the SVC stream to user i, that we call R. The selected unit acts as a relay: it receives the whole data stream (BL and all the ELs), and forward it over the SR link. The other users in the cooperative cluster only have to receive the data in the local SR network. Using the same notation of Section II-B1, $N-1$ users (N excluding the relay), that we call forwarders F, also receive and forward the BL. Notice that BL diversity is still exploited in this case, in the same way described in the previous section. Clearly, in a single time frame, user i consumes much more power than the other terminals. However, as the quality of the wireless links is dynamically changing over time, in a larger time interval every user will have the same probability to be involved as a relay. Therefore in average all the participants will achieve approximately the same power saving gain.

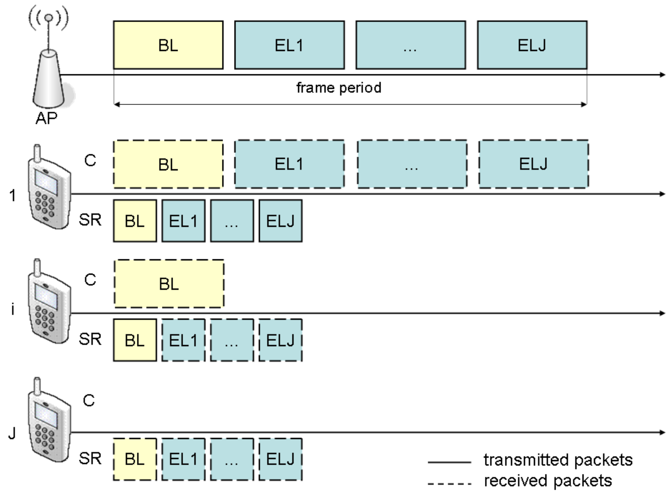

Fig. 4. Principle of cooperative reception of SVC substreams with one base layer and J enhancement layers, dynamic cellular channel allocation.

In this technique, the transmission is performed in two steps: first the unicast cellular reception according to the best channel, then the local SR communication. Notice that in the first step the video stream can be adjusted to the channel/user constraints according to the SVC principles. After that, existing P2P streaming algorithms can be used in order to perform the local SR broadcast in a *BitTorrent* fashion (see, *e.g.*, *SymTorrent* [7]).

III. ANALYTIC RESULTS

In this section, an analysis of the power saving gain of the techniques given in Section II is drawn. Notice that, since our reference unit is a time frame, we refer with the same meaning to power and energy consumption.

A. MDC Technique

Our target is to derive the power consumption P_{Coop}, normalized over a time frame, of the MDC cooperative scenario given in Figure 2. This is given by:

$$\begin{aligned} P^{MDC}_{Coop}(Z,J) \;&=\; \frac{1}{J}P_{rx,C} \;+\; \left(1-\frac{1}{J}\right)P_{i,C} \;+ \\ &+\; \frac{1}{J\cdot Z}\,P_{tx,SR} \;+\; \frac{J-1}{J\cdot Z}\,P_{rx,SR} \;+ \\ &+\; \left(1-\frac{1}{Z}\right)P_{i,SR}, \end{aligned} \tag{1}$$

where:

- Z is the ratio between the data rate used in the short-range link and the cellular link: $Z = \frac{R_{SR}}{R_C} \geq 1$;
- J is the number of terminals in the cooperative cluster;
- the parameters P_{rx}, P_{tx} are the power levels used by the inner circuitry of the devices to perform the operation of reception and transmission, respectively. P_{idle} denotes the power consumption during idle time, *i.e.*, when the devices are in *low-power* operation.

Notice we do not consider here issues such as delay and synchronization. An estimation of the power consumption per terminal of a cooperative cluster P_{Coop} can be easily obtained by replacing in (1) the power consumed for the reception P_{rx}, transmission P_{tx} and idle P_{idle} by network devices. This value can be directly compared to the power required in the non-cooperating scenario, for the same service quality, set to 1 by definition. More detailed results about the application of the technique in a dynamic scenario can be found in [2], showing very promising power saving potentials. A demo of the simulation model is freely available on the Internet [8].

B. SVC Techniques

1) SVC BL-RD: The technique, illustrated in Figure 3, refers to the general case where $N \leq J$. We assume that the BL and ELs are all of the same size. The power consumption is calculated in the same way described for MDC, according to the following relations:

$$\begin{aligned} P^{SVC1}_{Coop,i\leq N}(Z,J) &= \frac{2}{J+1}P_{rx,C} \;+\; \left(\frac{J-1}{J+1}\right)P_{i,C} \;+ \\ &+ \frac{2}{(J+1)\cdot Z}\,P_{tx,SR} \;+\; \frac{J-1}{(J+1)\cdot Z}\,P_{rx,SR} \;+ \\ &+ \left(1-\frac{1}{Z}\right)P_{i,SR}, \end{aligned} \tag{2}$$

and

$$P^{SVC1}_{Coop,i>N}(Z,J) = P^{MDC}_{Coop}(Z,J+1). \tag{3}$$

Hence, the average power consumption per terminal in this scheme is:

$$P^{SVC1}_{Coop}(Z,J,N) = \frac{N\cdot P^{SVC}_{Coop,i\leq N} + (J-N)\cdot P^{SVC}_{Coop,i>N}}{J}. \tag{4}$$

A case of special interest in this framework is diversity with $N = 2$, as the BL protection is still achieved by using two different communication paths. As it will be shown, this approach provides a good trade-off between robustness and power saving efficiency.

2) SVC DCA: With the same notation of Section III-B1, here we focus on Figure 4. In this scenario we have three different kind of cooperative agents: the relay (R), the terminals forwarding the BL (F), and the other terminals receiving only in the SR network (O). Therefore the power consumption can be calculated as following:

$$P^{SVC2}_{Coop,R}(Z,J) = P_{rx,C} + \frac{1}{Z}P_{tx,SR} + \left(1-\frac{1}{Z}\right)P_{i,SR}, \tag{5}$$

$$P^{SVC2}_{Coop,F}(Z,J) = P^{MDC}_{Coop}(Z,J+1), \tag{6}$$

$$P^{SVC2}_{Coop,O}(Z,J) = P_{i,C} + \frac{1}{Z}P_{rx,SR} + \left(1-\frac{1}{Z}\right)P_{i,SR}, \tag{7}$$

leading to an average power consumption per terminal:

$$P^{SVC2}_{Coop}(Z,J,N) = \frac{P^{SVC2}_{Coop,R} + (N-1)\cdot P^{SVC2}_{Coop,F} + (J-N)\cdot P^{SVC2}_{Coop,O}}{J}. \tag{8}$$

IV. PERFORMANCE EVALUATION

In this section, first we provide a performance analysis of the MDC technique. After that, we draw a comparison of the energy efficiency of different SVC techniques considering two different communication scenarios. A direct comparison of the MDC and SVC techniques, including a video quality evaluation of the two different schemes, is beyond the scope of this paper and currently under consideration. For all scenarios, the values about power consumption used in the calculations have been obtained from the specifications of network devices.

A. MDC Energy Efficiency

The energy saving efficiency of the MDC technique has been analyzed for different combinations of cellular and SR technologies. Figure 5 shows some results obtained by choosing WLAN (Wireless Local Area Network) or GPRS (General Packet Radio Service) for the cellular communication and WLAN, Bluetooth or UWB (Ultra Wide Band) for the SR. We notice that for all scenarios the normalized energy consumption dramatically decreases as the number of cooperating terminals increase. The power saving gain of cooperation is very high on the left side of the chart, then it tends to saturate. We notice that in this framework, the best results in terms of energy efficiency are achieved by the configuration GPRS/BT, leading to about 50% energy savings for only two cooperating terminals. This analytic result has been confirmed by tests in a real system, developed at Aalborg University [9].

B. SVC Scenario 1: WLAN/WLAN

Concerning the SVC techniques, a first series of results is obtained in the assumption of using WLAN technology for both the cellular and the SR communication. The normalized energy consumption versus number of cooperating terminals is obtained from the equations of Section III-B1 and III-B2, by replacing in the formulas the values about the actual power consumption of network devices. As in MDC, the energy consumption decreases as the number of terminals increase. In Figure 6 the power consumption per terminal is broken into several contributions determined by the cellular and the SR network. In this first scenario, the SR power consumption is highly determinant in the computation of the overall power budget. This is motivated by the fact that WLAN has not been conceived as a low power SR technology (therefore the impact of the power required for receiving and transmitting in the SR is significant).

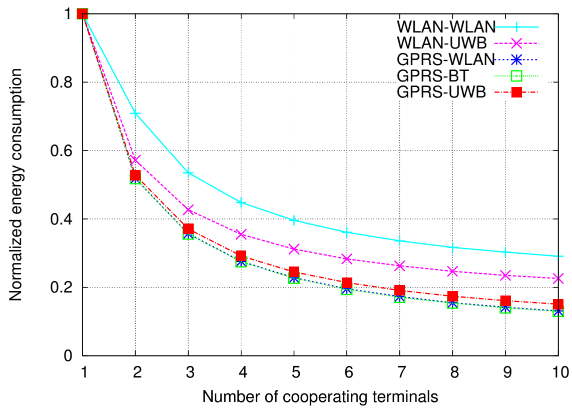

Fig. 5. Energy efficiency of MDC technique for different combinations of cellular/short-range communication platforms.

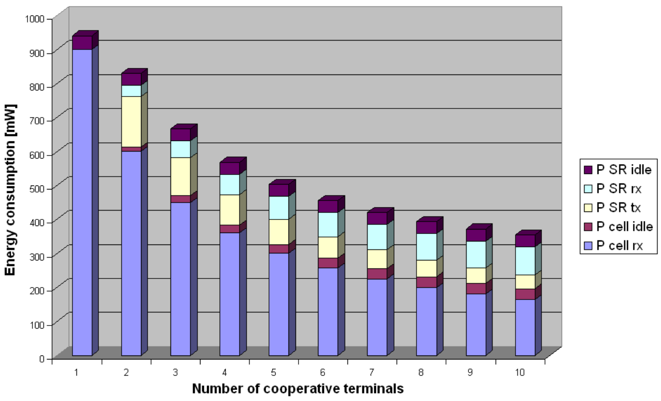

Fig. 6. Energy efficiency vs. number of cooperating terminals for SVC BL RD technique, case $N = J$, WLAN-WLAN.

In a second chart, Figure 7, a comparison of the power saving performance of the different SVC strategies discussed in Section II-B is shown. The most effective strategy in this scenario is *SVC DCA (N=R=1)*, leading to 0.535 energy consumption with 3 cooperating terminals. However this strategy does not actually exploit the cooperative architecture since it just allocates the best cellular channel and relays the information to the SR through a single user per time frame. For this strategy channel coding has to be used to protect the BL, as no diversity is exploited. It is perhaps more interesting to notice the good performance of *SVC BL-RD (N=2)*. In this case cooperation and SVC are coupled in a proficient

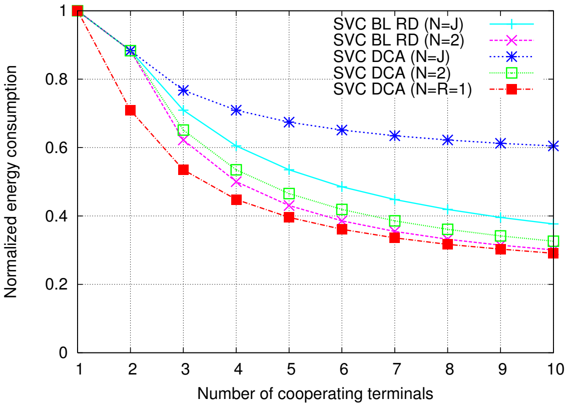

Fig. 7. Comparison of different SVC power saving techniques (scenario WLAN/WLAN).

way, using two different paths for the BL reception. The strategy may also provide a lower coding overhead. As it can be reasonably argued, *SVC DCA (N=J)* leads to poor power saving performance, since in this scheme the BL is received and forwarded by all the cooperating terminals even though a best channel has been selected.

C. SVC Scenario 2: GPRS/BT

In a second case scenario concerning the SVC techniques, we assume to exploit GPRS technology for the cellular reception and Bluetooth for the SR communication. A further series of results is obtained in these settings, and the energy efficiency is compared to the one given in Section IV-B.

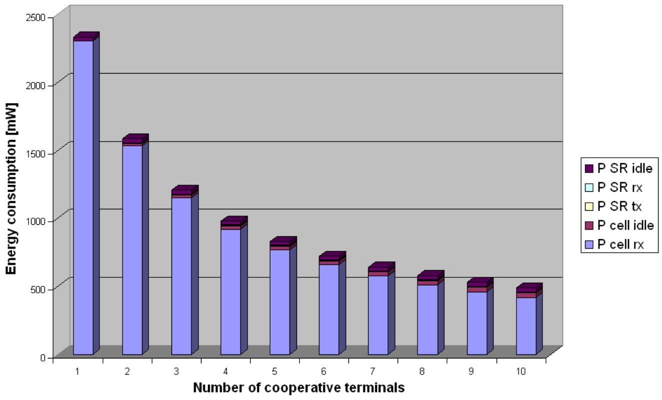

Fig. 8. Energy efficiency vs. number of cooperating terminals for SVC BL RD technique, case $N = J$, GPRS-BT.

In comparison to scenario 1, Figure 8 highlights two facts. First, a significantly higher power saving gain can be achieved in this configuration, as already shown in the MDC analysis. Second, the impact of the SR communication is much smaller than in Scenario 1 (Figure 6) with respect to the overall power budget. This can be motivated as Bluetooth is in fact a SR low-power technology. As for the cellular, GPRS is a 2G technology, but is capable to achieve a low power consumption during idle times (about 50 mW according to specifications of recent network interfaces for mobile handhelds). Figure 9 provides a comparison of the power saving performance of the different SVC techniques in this configuration.

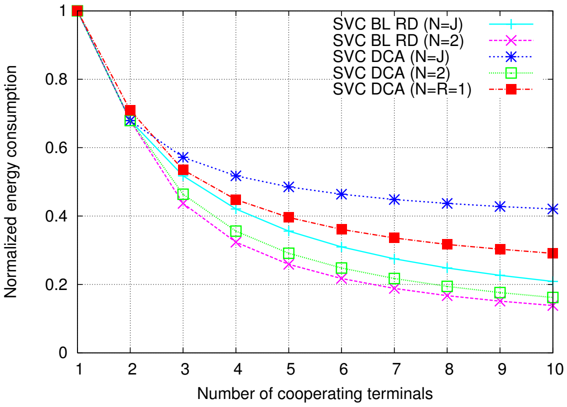

Fig. 9. Comparison of different SVC power saving techniques (scenario GPRS-BT).

This scenario, more suitable for cooperation, leads to significantly different results. The technique *SVC BL-RD (N=2)* achieves the best power saving results, showing highly reduced energy consumption of 0.437 for 3 cooperating terminals. *SVC DCA (N=2)* approaches this result. Therefore two dimensional diversity is shown to be the most appropriate choice in this scheme. We notice that also *SVC BL-RD (N=J)* results in a good power saving performance. Due to its robustness, this strategy could be well suited for highly error-prone environments. We also point out that the best technique in Scenario 1, *SVC DCA (N=R=1)*, performs very poorly in Scenario 2. This fact shows that the technology is a crucial factor when choosing the appropriate energy saving technique. *SVC DCA (N=J)* is the less efficient strategy for the same reasons given in Scenario 1.

V. DISCUSSION AND CONCLUSION

In this paper we described some novel approaches for video streaming and multimedia applications over wireless networks. The concept of combined cellular-SR network architecture has been coupled with two different video coding schemes, MDC and SVC. The introduced cooperative techniques have been conceived for the goal of achieving robust transmission over wireless channels and energy efficiency. The MDC scheme, by splitting the data stream into independent descriptors, is a natural approach to implement the cooperative architecture of Section I. For this reason, it has been already taken into account in several works of research about cooperation. In this paper, after discussing a MDC power saving technique in Section II-A, we have shown promising results for different combinations of cellular/SR technologies. In our analysis, the best energy saving scenario was GPRS/BT, while upcoming SR low power-high data rate technologies (such as Bluetooth 3.0 or UWB) are expected to be even more efficient for the considered framework. However, in MDC, the cost of having independent descriptors is paid by means of reduced coding efficiency. In this study, we introduced and discussed novel cooperative strategies based on SVC. We motivate this choice as SVC is being increasingly used in video streaming applications over wireless networks and it has been recently added to the standard H.264/AVC. The main difference with MDC is the introduction of a hierarchical structure between the substreams. Here we coupled this approach with cellular-controlled SR cooperation. The first SVC strategy, described in Section II-B1, is a simple variation of the MDC technique. In this scheme, the BL is protected against transmission errors by diversity, leading to possible elimination of channel coding schemes (FEC/ARQ) usually required in SVC. As in the MDC case, the major advantage of the technique is energy saving, achieved by switching to low power mode the devices during idle times. The second SVC strategy, described in Section II-B2, requires cognition of the channel conditions at the transmitter. In this assumption, the data stream is sent dynamically to the user in the cooperative cluster featuring the best cellular channel. After that, available P2P streaming algorithms can be used to perform the local SR exchange. Also in this case, the BL reception is ensured by diversity. The strategies have been analyzed in two different cooperative scenarios, WLAN/WLAN and GPRS/BT. In both cases we have shown that the energy consumption can be significantly reduced respect to the normal autonomous operation. Moreover, by comparing the two scenarios we noticed that the energy efficiency is significantly dependent on the technology settings. As previously suggested by the MDC analysis, the best results were achieved in the configuration GPRS/BT. This case study also highlighted that two-dimensional diversity is the best choice for implementation in a real system. Besides theoretical analysis, the MDC technique has been tested in a real system.

The testbed, developed at Aalborg University by using GPRS technology for the cellular communication and Bluetooth for the SR, has confirmed a that a power saving gain of about 50% can be achieved with only two cooperating terminals [9]. The cellular controlled short-range architecture for video streaming applications has been also recently studied in [11]. Furthermore, a possible application using DVB-H (Digital Video Broadcast - Handheld) for the cellular communication and Bluetooth for the SR, has been analyzed in [10]. Future work including a video quality evaluation of the MDC and SVC schemes, and a direct comparison of the power saving techniques discussed in this paper is currently under consideration.

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