Abstract—In this paper we develop and analyze energy-efficient cooperative techniques for multimedia applications over wireless networks. The composite cellular-short-range network architecture is explored by using multiple description coding and scalable video coding schemes. In order to provide an overall and fair assessment of the schemes, different approaches are evaluated and discussed. The techniques are compared not only in terms of their energy gain with respect to noncooperative (autonomous) operation but also considering the quality of the delivered video signal.

I. INTRODUCTION

One of the most challenging tasks of future high-performance communication networks is efficient delivery of rich-content information. Transmission of multimedia data (e.g., video streaming, etc.) over wireless networks is a particularly demanding operation because of the impairments imposed by the radio channel as well as the energy limitations of the hand-held devices. Anyway, already today we are witnessing the emergence of new mobile services involving transmission of video signals, e.g., TV-on-mobile and video-on-demand services. In the future, such services are expected to increase in number and quality. However, real-time video streaming imposes strict requirements to the signal to be delivered (e.g., delay and packet loss), in especial taking into account the highly dynamic characteristics of the wireless channel and network. The main challenges to be addressed are limited bandwidth, channel characteristics (attenuation, fading, noise, interference), large heterogeneity of wireless devices and their inherent energy limitations. Therefore transmission protocols must be carefully designed to deal with the characteristics and limitations of the system. An effective solution to cope with wireless channels is scalability, whereas the video stream is scaled depending on the availability of network resources. The advantages include adaptivity to heterogeneity of terminals and network platforms, low latency, low complexity and low handoff dropping.

Among the mentioned challenges, we particulary highlight the fact that battery-driven wireless devices are seriously energy limited, and such a problem is not likely to be solved in the foreseeable future. The trend of providing better services involves, among others, supporting higher data rates and larger displays, increasing naturally the power requirements of terminals. Moreover, advances in battery technology cannot keep up with the steep increase of power consumption that we observe in each new generation of wireless devices. A possible solution to address the energy problem is to exploit cooperation among wireless terminals. This approach, known as cellular-controlled short-range communications, exploits the cooperation between the cellular (C) and short-range (SR) network platforms [1], as illustrated in Figure 1. Mobile devices in close proximity form a cooperative cluster over short-range links while they can also be connected to the cellular network. The potential of this novel approach has been recently discussed in several works, e.g., [2]. This centralized-distributed architecture exploits the fact that transmitting bits over short-range links is considerably more energy efficient than transmitting them through cellular links.

Fig. 1. Cooperative cellular-controlled short-range network architecture (only two wireless devices shown).

In this paper we aim to combine the flexibility of modern video coding techniques such as multiple description coding (MDC) and scalable video coding (SVC) with the high power...
saving potentials of cooperative techniques. In order to evaluate and compare the performance of both schemes in a fair manner, we consider not only the energy saving capabilities but also their achieved quality of service.

II. ENERGY-EFFICIENT COOPERATIVE TECHNIQUES WITH MDC AND SVC

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

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. MDC provides a way to enhance error resiliency of the video stream in order to cope with the wireless fading channel. This operation is achieved without using additional error correction techniques (FEC/ARQ), hence the presence of a feedback channel is not mandatory. The cost of MDC is the insertion of a certain amount of redundancy between descriptors.

The property of independence between different descriptors makes this technique particularly suitable for the application of cooperative techniques. Relying on the hybrid network architecture described in [1] we address the goal of power saving in video streaming applications. A brief introduction of the MDC power saving technique is given as follows:

- 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. In particular, this study is based on WLAN (Wireless Local Area Network) technology for both the cellular and the SR range communication.

We assume that the service is split into substreams according to the MDC principles and 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. We distinguish two possible operation modes:

- **Non Cooperative Operation** (self-sustaining or autarky). The $J$ terminals do not cooperate and receive all the $J$ substreams with autonomous operation over the downlink channel;
- **Cooperative Operation** (terminals cooperate with each other). Each unit receives only one out of the $J$ substreams and forward it to the other $J - 1$ cooperative terminals over the short-range communication link (SR exchange).

In the cooperative case, we will show that the power consumption of wireless terminals can be 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 is lower. An illustration of this technique is provided in Figure 2.

B. SVC Techniques

Layered Coding (LC) is analogous to MDC. The main difference is the introduction of a hierarchical structure between the substreams. The video signal is split into a base layer (BL) and several enhancement layers (EL). The BL provide coarse video quality, while the EL can be used progressively to refine the achieved quality, thus providing scalability. In this scheme the reception of the base layer is crucial, therefore BL must be protected against transmission errors by channel coding. The concept of LC is more commonly referred as Scalable Video Coding (SVC), which has been recently standardized as an extension of the H.264/AVC [5]. A more detailed comparison with MDC can be found in [4].

SVC has been conceived in order to provide scalability and flexibility for video streaming services over IP-based networks [6]. In particular, in wireless networks, it is an efficient way to cope with the large heterogeneity of channels, communication protocols, and device capabilities. By using SVC, the data stream can be tailored according to the constraints of the channel and the user requirements through bitstream rate adaptation. Three different levels of scalability are provided: SNR, temporal and spatial scalability. The smallest set of information that can be decoded independently is a frame slice. In this study, we aim to explore the potentials of SVC for cooperative video services supported over wireless networks. The goal of the strategies is 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 terminals, equal to the number of SVC enhancement layers (leading to overall number of substreams). As the BL reception is crucial in SVC, in this scheme we assume that terminals receive the BL and forward it over the SR link. On the other hand, the ELs are received separately and forwarded by all cooperating terminals, as in the MDC framework. In this way the BL is secured against transmission errors by diversity. In comparison with 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 coding efficiency, large applicability due to standardization [5], and high flexibility which can be provided towards a variety of heterogenous terminals. 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 can be avoided.

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 and transmits the SVC stream to user , that we call . 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-B.1, users (excluding the relay), that we call forwarders , also receive and forward the BL. Notice that BL diversity is still exploited in this case, in the same way described in Section II-B.1. Clearly, in a single time frame, user 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.

### 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 , normalized over a time frame, of the MDC cooperative scenario given in Figure 2 (we do not consider here issues such as delay and synchronization). This is given by:

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

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 periods, i.e., when the devices are in low-power operation.

Thus, 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 with the power required by the non-cooperating scenario, for the same service quality, set to 1 by definition. More detailed results about the application of this technique in a dynamic scenario can be found in [2], by means of an agent-based simulation model. A demo is freely available on the Internet [8].

B. SVC Techniques

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

\[
P_{SV C1_{Coop,1\leq N}}(Z, J) = \frac{2}{J+1} P_{rx,C} + \left( \frac{J-1}{J+1} \right) P_{i,C} + \\
\frac{2}{(J+1) \cdot Z} P_{tx,SR} + \frac{J-1}{(J+1) \cdot Z} P_{rx,SR} + \\
\left( 1 - \frac{1}{Z} \right) P_{i,SR}
\]  

(2)

and

\[
P_{SV C1_{Coop,1\leq N}}(Z, J) = P_{Coop, O}(Z, J + 1)
\]  

(3)

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

\[
P_{Coop, O}(Z, J) = \frac{N \cdot P_{SV C1_{Coop,1\leq N}}(Z, J) + (J-N) \cdot P_{SV C1_{Coop,1\leq N}}(Z, J)}{J}
\]  

(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 we will show, this approach provides a good trade-off between robustness and power saving efficiency.

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

\[
P_{SV C2_{Coop,F}}(Z, J) = P_{rx,C} + \frac{1}{Z} P_{tx,SR} + \left( 1 - \frac{1}{Z} \right) P_{i,SR}
\]  

(5)

\[
P_{SV C2_{Coop,O}}(Z, J) = P_{Coop, O}(Z, J + 1)
\]  

(6)

leading to an average power consumption per terminal:

\[
P_{Coop, O}(Z, J) = \frac{P_{SV C2_{Coop,O}}(Z, J) + (N-1) \cdot P_{SV C2_{Coop,F}}(Z, J) + (J-N) \cdot P_{SV C2_{Coop,O}}(Z, J)}{J}
\]  

(8)

IV. OVERALL PERFORMANCE EVALUATION

In this section, we provide an overall performance analysis of the MDC and SVC techniques considering both power saving gain as well as coding efficiency.

A. Power Saving Gain

1) MDC Technique: The power saving gain of the MDC technique has been analyzed using different combinations of cellular and SR technologies. Figure 5 shows some results obtained with different access technologies, namely WLAN (Wireless Local Area Network) and GPRS (General Packet Radio Service) for the cellular communication and WLAN, Bluetooth and UWB (Ultra Wide Band) for the SR communication. We notice that for all scenarios the normalized energy consumption dramatically decreases as the number of cooperating terminals increase. The differential power saving gain versus number of units is very high in the left side of the chart, then it tends to saturate. The best results in terms of energy efficiency are achieved by the configuration GPRS/BT, leading to more than 50% energy savings with only two cooperating terminals. This analytic result has been confirmed by tests in a real system, developed at Aalborg University. It is also worth noticing that, in this framework, already a small number of cooperating devices (typically 2-3) results in significant reductions in the energy requirements.

Fig. 5. Energy efficiency of MDC technique for different combinations of communication platforms.
2) 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 by replacing in the formulas of Section III-B.1 and III-B.2 the actual values about power consumption of network devices. As in the MDC case, the energy consumption decreases as the number of terminals increases. In Figure 6, a comparison of the power saving performance of the different SVC strategies discussed in Section II-B is shown.

![Fig. 6. Comparison of different SVC power saving techniques (scenario WLAN/WLAN).](image)

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 fully exploit the cooperative architecture since it just allocates the best cellular channel and relay the information to the SR through a single user per time frame. Moreover, channel coding has to be used as no diversity is exploited. We notice instead the good performance achieved by SVC BL-RD \((N = 2)\). In this case cooperation and SVC are coupled in a proficient way, by using two different paths for the BL reception. This strategy may also provide lower coding overhead (no feedback channel is required). As can be reasonably argued, SVC DCA \((N = J)\) leads to poor power saving performance, since in this scheme the BL has is received and forwarded by all the cooperating terminals even though a best channel has been selected.

3) SVC Scenario 2 - GPRS/BT: In a second scenario regarding the SVC techniques, we assume to exploit GPRS technology for the cellular reception and Bluetooth for the SR communication. A significantly higher power saving gain can be achieved in this configuration, as previously shown in the MDC analysis. This can be motivated as Bluetooth is in fact a SR low-power efficient technology and GPRS cellular is capable to achieve a low power consumption during idle times (about 50 mW from the specifications of recent network interfaces for mobile handhelds). Figure 7 provides a comparison of the power saving performance of different SVC techniques in this configuration.

![Fig. 7. Comparison of different SVC power saving techniques (scenario GPRS-BT).](image)

It is interesting to notice that 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 a highly reduced energy consumption of 0.437 for 3 cooperating terminals. SVC DCA \((N = 2)\) approaches this result. Therefore, two dimensional diversity is the most appropriate choice in this configuration. We notice that also SVC BL-RD \((N = J)\) results in a good power saving performance. Due to its robustness, this strategy could be used in highly error-prone environments. Finally we point out that the best technique in Scenario 1, SVC DCA \((N = R = 1)\), performs very poorly in Scenario 2. This fact highlights that technology settings are 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.

B. Coding Efficiency

In this section we provide a comparison of the coding efficiency of MDC and SVC. We will analyze the video quality achieved by the two schemes, given that the same BW and channel conditions are available (MDC with \(J\) substreams vs. SVC with one BL and \(J\) ELs). In this work we have used frame-based MDC, where consecutive frames are put into \(J\) substreams in a round robin fashion such that the \(i\)-th substream contains frame \(i\), \(J + i\), \(2J + i\) and so on \([10]\). Each substream is then encoded using standard non-scalable video codec e.g., H.264/AVC and each of the substreams can be decoded independently without the information carried by other substreams. Eventhough MDC introduces independently decodable substreams, it is achieved at the price of lower compression efficiency and higher bandwidth usage than with layered coding where some dependency between layers exists. Here we use the recently standardized scalable extension of
H.264 (SVC) to achieve layered coding. Encoded SVC stream includes $J$ temporal layers and the length of Group of Picture (GOP), in this case is $2^{J-1}$. The relationship between the original sequence, MDC and SVC streams are illustrated in Figure 8 for GOP = 8.

![Fig. 8. Temporal allocation of frames into $J$ substreams (MDC) and $J$ layers (SVC), $J = 4$ and GOP = 8.](image)

To evaluate the coding efficiency and compare the quality achieved with MDC and SVC, we generated both MDC and SVC streams at same bitrate (maximum 512 kbps) and with the same amount of substreams/layers ($J = 6$). We calculated the quality of the received video signal for different subsets of substreams/layers using PSNR (Peak-Signal-to-Noise-Ratio) metric, which is a common objective quality metric for video. In a situation where a substream of MDC or layer of SVC is missing, some frames are also missing. When calculating PSNR of the reconstructed video, the missing frames are filled by copying the last successfully received frame until the next frame is received. The same method is used for both reconstructed MDC and SVC. In Figure 9 and 10, the PSNR measurements versus frame rate of the reconstructed sequence for the foreman and container sequences (CIF resolution) using $i$ ($i=1...J$, $J=6$) substreams or layers are illustrated. The bitrate for each substream and layer is the same for both MDC and SVC (total bitrate / $J$). As it can be observed from the figures, MDC is better when a small number of substreams is received. This is determined by the different default parameters settings at the encoder which has been illustrated in Figure 8. However, the coding efficiency of SVC outperforms MDC when a sufficient number of substreams (namely, more than 3) are received, and the difference increases as more substreams/layers are added. The difference comes from the redundancy between MDC substreams. In SVC the redundancy between layers is smaller since prediction methods are used between layers in order to improve the coding efficiency. However, a loss of layer from SVC stream degrades the quality of reconstructed sequence greater than a loss of substream from the MDC stream. This comes from the frame rate characteristics of the SVC stream where a loss of layer halves the frame rate of the reconstructed sequence. For high motion sequences like foreman, this degradation is even greater than for slow motion sequence like container.

![Fig. 9. PSNR vs. frame rate for foreman sequence using MDC and SVC.](image)

![Fig. 10. PSNR vs. frame rate for container sequence using MDC and SVC.](image)

V. Discussion and Conclusion

In this paper we studied some novel cooperative approaches for video streaming and multimedia applications over wireless networks. The underlying network architecture consists of a composite cellular-short-range network, which was coupled with two different video coding schemes, MDC and SVC. The goal of such a cooperative approach was two-fold, namely achieving robustness against transmission errors (hence guaranteeing high signal quality at the receiving end) as well as
reducing the energy expenditure of the wireless terminals to a minimum. MDC divides the data stream into a number of independent descriptors, though its coding efficiency is not so high due to the considerable redundancy existing between descriptors. Unlike MDC, SVC has a hierarchical structure in its descriptors, typically called layers. SVC techniques are more flexible and efficient that the MDC counterparts, and the inclusion of SVC techniques into the H.264/AVC standard has made these techniques very popular. A first cooperative strategy was developed using MDC, and analyzed for different combinations of cellular/short-range technology sets. Then, two cooperative strategies were considered for the SVC scheme. In the first technique, the base layer is protected against transmission errors by diversity, with no need for additional coding (FEC/ARQ) as usually required in SVC. As in the MDC scenario, the major advantage is energy saving, achieved by switching to low power mode the devices during idle times. The second strategy assumes that channel state information is known at the transmitter. Thus, the data stream is dynamically sent to the user in the cooperative cluster which has the best available cellular channel. After that, some P2P algorithms are used to perform the local SR data distribution. Also in this second case, the BL reception is ensured by diversity.

Analytic results based on power consumption of network devices show that both MDC and SVC techniques have a high potential to reduce the energy requirements of wireless devices. The MDC technique achieves a slightly better performance due to the property of independence between descriptors. However, the SVC techniques are capable to achieve a comparable performance in terms of energy savings while outperforming MDC in terms of coding efficiency. Therefore, we highlight the high potential of combining SVC and cooperation as focus of future research work. Note that the energy saving performance strongly depends on the pair of access technology employed for the short-range and cellular links, as well as on the used cooperative strategy. In addition to the energy saving capabilities, a complete characterization of the performance requires also the quality analysis of the video streaming delivered through the cooperative architecture. It was shown that also in terms of received signal quality (PSNR) the SVC schemes outperforms MDC for a wide range of frame rates. The difference becomes more pronounced as the frame rate increases. In particular, the results on quality presented in section IV-B suggest that a different cooperative scheme shall be considered when using SVC. As a matter of fact, SVC does not achieve a good performance (framerate, PSNR) when a small number of substreams is received. However, the performance curves presented in Figures 5, 6 and 7 show that the power saving gain of cooperation is really beneficial already for small groups of users (then the gain tends to saturate). Therefore, when using SVC, it would make sense to send multiple substreams to each user in the cooperative cluster (e.g., 2 – 3 streams per user) so that a high video quality could be achieved already with a small number of receiving terminals. This may allow the SVC technique really outperform MDC. For instance, assume that we have three cooperating users. The MDC technique will result in three received substreams, leading to power saving gain for these three users, depending on the technology, and the ratio framerate/quality \((framerate = 15fps, PSNR = 34dB)\) according to Figure 9. The SVC technique using one substream/user still lead to power saving gain for three users, but rather poor framerate/quality ratio \((framerate = 4fps, PSNR = 32dB)\). On the other hand, if we use the SVC technique by sending two substreams/user we achieve the same power saving performance and optimal framerate/quality ratio \((framerate = 30fps, PSNR = 41dB)\). This configuration is even better than (hypothetical) MDC using two substreams/user, leading to \((framerate = 30fps, PSNR = 36dB)\). Notice that the analytic results provided throughout this paper still holds if we change what we called as substream (or layer) with cooperating unit, a basic cooperative descriptor including single or multiple video substreams. We argue that, in the future, the number of streams/cooperating user as well as the video coding scheme to be utilized shall be dynamically adjusted at the transmitter depending on circumstance. In conclusion, in this paper we evaluated the suitability of cooperative schemes based on a composite (distributed/centralized) architecture to deliver efficiently video streaming contents. This overall evaluation comprised both quality performance as well as gain in energy requirements (compared to a noncooperative case). Results indicate that modern coding schemes such as MDC and SVC are both suitable for such task. Further investigation needs to be carried out in order to optimize the cooperative strategy for different coding schemes and scenarios.

REFERENCES