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COOPERATIVE VIDEO STREAMING WITH DYNAMIC COMPRESSION AT THE TERMINAL NODES

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ABSTRACT

Media content distribution constitutes a growing share of the services on the Internet. In recent years methods for cooperative media distribution has been a research area with high activity. Concurrently wireless internet connections have emerged. Wireless connection technologies, e.g. Wimax, have properties which make them suboptimal for cooperative distribution. In particular, the asymmetric relationship between the uplink and the downlink bandwidth makes the cooperative distribution difficult. Today two distinct source coding approaches are used; Layered Coding (LC) and Multiple Description Coding (MDC). A promising concept, termed MDC with Conditional Compression (MDC-CC), has been proposed in [1]. MDC-CC essentially acts as an adaptive hybrid between LC and MDC and is particularly interesting when combined with cooperative distribution. In this paper a scheme utilizing the concept of MDC-CC is proposed. The functionality of the scheme has been described and performance estimates using different distributions of redundancy has revealed that the proposed scheme has great potential.

1. INTRODUCTION

Distribution of media is a rapidly increasing part of the total Internet traffic. In general, services involving video distribution have very high bandwidth requirements. The tendency is that more media services are distributed via the Internet and, in the near future, via wireless connection technologies, e.g Wimax. In such networks, the last hop offers low reliability and the uplink and downlink are highly asymmetric. This results in a generally low and possibly varying QoS [2, 3].

Cooperative distribution is one way to overcome the challenge of high bandwidth requirements. In a cooperative approach, users that request the same data at the same time receive disjoint parts of the requested data and cooperatively distribute it among themselves. This reduces the cost of distribution for the provider because the bandwidth consumption of the source is decreased. However, the wireless environment creates largely asymmetric link parameters, which poses a great challenge when combined with cooperative distribution.

The goal is to provide the best possible quality, for the media decoded at the receivers. This introduces the need for coding schemes that define how the media is represented in discrete data blocks. The two coding schemes that are used today are Multiple Description Coding (MDC) and Layered Coding (LC). MDC [4] encodes a media stream into multiple non-prioritized descriptions. From any description a low quality replica of the original content can be constructed and every additional description will improve the quality. As the descriptions are self-sufficient, they introduce a large amount of redundancy. This makes MDC error resilient, but requires a large bandwidth which is not always available, especially not over the wireless links. LC [5] encodes the media into a base layer and a number of enhancement layers. The enhancement layers depend on the base layer, which allows the information in the enhancement layers to be compressed. In this way the encoded media requires less bandwidth compared to MDC, but it is also more susceptible to errors and is therefore not suited for an error prone wireless channel.

Thus MDC and LC are schemes suited for different scenarios in terms of available bandwidth and error rate. In [1] MDC with Conditional Compression (MDC-CC) is introduced. MDC-CC is a scheme that is in between MDC and LC and thus attempts to offer a combination of the advantages of MDC and LC. This is achieved by removing parts of the redundant data introduced by MDC only when this data is rendered useless at the receiver, e.g. when another description has been received. MDC-CC efficiently removes redundancy and operates in a cross-layer manner by adaptively alternating between MDC and LC via the compression of the descriptions. This allows MDC-CC to offer the same error resilience as MDC when the number of errors in the network is the primary constraint and as effective compression as LC when bandwidth is the dominating delimiter. The distribution in the network is usually impacted by both the bandwidth limitation and the errors. In this case MDC-CC can offer a redundancy level in between MDC and LC, thus potentially outperforming both of them: MDC by the higher rate and LC by the error resilience.

Compression of descriptions requires knowledge of the network. This knowledge can be based on feedback from the receiving node or by probing the receiving node for information, where the use of feedback will introduce the least amount of additional transmissions in the network. In our scheme we consider a setting with randomly varying link bandwidths in which the receiving nodes do not provide an explicit feedback for the status of the received descriptions. Therefore, the nodes should decide whether to compress the description based solely on the link statistics. A compressed description has higher chance to get to the destination on time, as it requires less bandwidth; however, a compressed description is of no use if the other descriptions are not received. In this paper we explore this trade off and provide probabilistic optimization of the compression strategies.

The remainder of the paper is organized as follows. Section 2 introduces the scheme utilizing the concept of MDC-CC. A scenario on which the scheme is applied is analysed in section 3. Performance is evaluated and compared to that of LC and MDC in Section 4. The final conclusions are drawn in Section 5.

2. SYSTEM MODEL. THE PROPOSED SCHEME

The descriptions in a description set are created from a Group Of Frames, GOF. Each GOF is encoded using MDC-FEC, which converts a layered representation of the media into multiple de-

scriptions using Reed-Solomon codes [6]. By protecting each layer with FEC, MDC-FEC is able to convert a layered media stream into multiple descriptions. The FEC is encoded using (n, k) Reed Solomon codes, where k is the length of the data and n the total codeword length. In this way the original data can be reconstructed from any k symbols of the n symbol codeword. When the FEC is appended the resulting descriptions are created by including one part from each layer. Figure 1 shows an example of this for three layers and three descriptions.

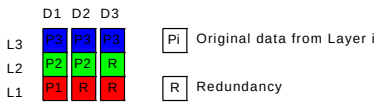

Figure 1. Descriptions are created using the principle of MDC-FEC.

The base layer, Layer 1, must be decodable if just one description is received and is therefore encoded with the strongest FEC. The strength of the FEC decreases up through the enhancement layers. Therefore the second layer (first enhancement layer) is decodable when any two descriptions are received and the k-th layer is decodable when any subset of k descriptions is received.

It is now possible to identify the possibilities of compression in MDC-FEC. If a description is successfully received, e.g. D_2, Layer 1 is already decodable regardless of what is received in addition. Hence, the cells of the two other descriptions holding data for Layer 1 are useless and can be removed.

Consider the example of cooperative distribution of two descriptions illustrated in Figure 2. The descriptions are created by the media source from its two layers of data packets using the procedure described earlier (see Figure 1). In Figure 2, data packets and redundancy packets are respectively stamped with the letters "P" and "R". Furthermore, Layer 1 packets are colored in red, while Layer 2 packets are colored in green. The delivery consists of three steps. In the first step, the source creates the descriptions D_1 and D_2 and delivers them individually to the Nodes 1 and 2, respectively. After this step, with the received information (description), each of the nodes decodes the data of Layer 1 (packet "P1" in red, in the figure). In the second step, the nodes remove this packet from their corresponding descriptions, after which they are left with packet "P1" in green (at Node 1) and packet "P2" in green (at Node 2). In the third step, the nodes exchange the packets P1 and P2 of Layer 2 between them. Hence, the nodes can send less information (compared to sending the whole description) by removing the information in the description that the recipient already has. This idea of compression before forwarding is suited to the wireless systems. Due to the asymmetry of typical wireless connections, if the downlink capacity is fully utilized it is not possible to forward the same amount of data via the uplink. Hence, in such cases, cooperative distribution is only possible if compression is performed.

In the general case, in the first step, n descriptions are sent to n different nodes, connected in a mesh. Consider the reception of node 1: it already has the layer one, it needs one more packet to decode the second layer and, in general, $k-1$ more packets to decode the $k-$th layer. For the example on Figure 1, assume that the node $i(i = 1, 2, 3)$ has received the $i-$th description and observe the reception at node 1. In the ideal compression scheme, node 2 sends only information on the Layers 2 and 3 and the node 3 sends only information on the Layer 3. However, this ideal compressing scheme fails to deliver good distortion when the available bandwidths of the connections in the mesh is not sufficient. For example, receiving Layer 3 information from Node 3 is useless if the information from the Node 2 is not received. In general, if there is an uncertainty about the bandwidth of a link, a node should request more redundancy in the information from stronger links in the mesh in order to make the overall system operation robust to packet loss. Stated shortly, a smaller packet has a higher probability to get across the network, but its utility at the end receiver depends on whether information has been received from the other cooperating nodes. Therefore, when requesting, each node calculates the expected distortion of all possible redundancy distributions based on the applied source coding and an estimate of the bandwidth to the other nodes in the mesh. How to obtain such a bandwidth estimate is outside the scope, but this problem has been thoroughly treated in the work of others [7, 8].

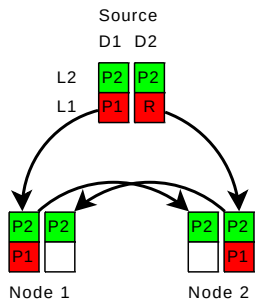

Figure 2. Two nodes receive data from a source and exchange a compressed description in order to efficiently improve the media quality.

The objective of the analyzed scheme is to cooperatively distribute descriptions between a set of nodes in a small mesh. Each node chooses the redundancy that yields the lowest expected distortion, and requests descriptions with the corresponding compressions at all other nodes in the mesh. This procedure is performed for each description set. It might not be optimal to request an updated redundancy distribution for each description set. Instead the nodes could request an update e. g. every 10th description set, or when the update yields an improvement in expected distortion above a certain threshold. Nevertheless, in the rest of this paper we update for each description set.

3. ANALYSIS

The performance of the proposed scheme is highly dependent on the amount of redundancy in each description. In order to sustain acceptable performance, redundancy is required whenever data is lost or delayed beyond the decoding deadline. However, the available end to end bandwidth of a wireless link is not static. Nor can it be expected that the peer network is homogeneous with respect to available bandwidth. This makes a fixed selection of the amount of redundancy, determined from the initial conditions, suboptimal. Instead each node should determine an appropriate amount of redundancy for the descriptions received from the mesh. Hence the problem is to select the distribution of redundancy that minimizes the expected distortion, $E[Z]$, based on an estimate of the available bandwidth for each peer connection. This section will explain the calculations that constitutes the basis of the scheme.

The distribution of redundancy is illustrated as in Figure 3, where each square represents a layer in a description. A square is referred to as a cell and each requested cell is filled with a color. Non filled squares denotes cells that are not requested. Thus an example of requested descriptions with no redundancy is given in Figure 3.

In a system with n descriptions, the receiver will experience one of $n+1$ distortion levels at each GOF, Z_i, $i = \{0, 1...n\}$, where the index denotes the number of decodable layers. Each

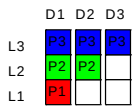

Figure 3. Example of descriptions requested without redundancy.

distortion level occurs with some probability, $P(Z_i)$. Hence, the expression of the expected distortion is given by equation (1).

$$E[Z] = \sum_{i=0}^{n} P(Z_i) \cdot Z_i \tag{1}$$

where Z_i is the distortion for i decodable layers and is solely related to the source coding, not depending on the redundancy. $P(Z_i)$ however, is a function of the redundancy and the method for constructing the descriptions, thus, to minimize $E[Z]$ the relationship between $P(Z_i)$ and the requested descriptions must be determined.

3.1. Error Probabilities

To estimate whether a description is received within the decoding deadline, knowledge of the available bandwidth must be available. We assume that adaptive modulation and coding is applied on the wireless links. Hence it can be assumed that packets are always received correctly, however their rate is variable, which results in variable overall bandwidth. Due to the dynamic nature of a wireless link it is desired to have an estimate of the instantaneous available bandwidth. However, estimating the bandwidth is outside the scope of this work. Instead we assume that the estimate is available to the scheme and that it is normally distributed with the true bandwidth as mean and a certain variance, σ^2. This entails that the conditional distribution of the true bandwidth, given a certain estimate, has variance σ^2 and the estimate as mean. This distribution can be utilized to determine the probability that the link carrying a description, has enough bandwidth to deliver the description within the decoding deadline. The cdf of the distribution of the true bandwidth evaluated at the required bandwidth gives the probability of insufficient bandwidth for delivery within the decoding deadline. Thus, one minus this value is the probability of success. The probability $P(D_j)$ of receiving description j within the deadline is expressed as:

$$P(D_j) = 1 - \int_0^{B_{Dj}} \frac{1}{\sqrt{2\pi} \cdot \sigma} \cdot e^{-(B_{Dj} - B_j)/2\sigma^2} \, dB_j \tag{2}$$

where:

B_{Dj} is the bandwidth required to deliver description j

B_j is the bandwidth of the link carrying the j'th description

From this expressions for different $P(Z_i)$, given the redundancy distribution, can be found. Based on the principle of layered coding the following general rule for the occurrence of the distortion Z_i can be outlined.

Distortion Z_i is achieved when layers $\{1, 2, ..., i\}$ are decodable and layer i+1 is not decodable.

In a system with n layers, Z_n and Z_0 are special cases where the irrational part of the general rule is omitted.

3.2. Example with no Redundancy

Consider the example in Figure 3, where the set of descriptions has no redundancy. The probability of successfully receiving description j is denoted $P(D_j)$. The probabilities, $P(Z_i)$ $i = \{0, 1, 2, 3\}$ can now be derived, using the general rule described in section 3.1. The probability of having zero decodable layers, $P(Z_0)$, only depends on Layer 1 (row 1), because all other layers will be useless if this layer is not present. Since all redundancy in Layer 1 has been removed, only description 1 is able to deliver the cell needed to decode this layer. Hence $P(Z_0) = 1 - P(D_1)$. Considering $P(Z_1)$, Z_1 is achieved when Layer 1 is decodable and Layer 2 is not. Therefore $P(Z_1) = P(D_1)(1 - P(D_2))$. With the same reasoning $P(Z_2) = P(D_1)P(D_2)(1 - P(D_3))$. Z_3 is achieved when all descriptions are successfully received. These probabilities are listed in equation (3).

$$\begin{aligned}
P(Z_0) &= 1 - P(D_1) \\
P(Z_1) &= P(D_1)(1 - P(D_2)) \\
P(Z_2) &= P(D_1)P(D_2)(1 - P(D_3)) \\
P(Z_3) &= P(D_1)P(D_2)P(D_3)
\end{aligned} \tag{3}$$

The expected distortion from equation (1) can be calculated using the rate distortion function for the applied source code and a combination of the equations in (3) and (2). $E[Z]$ can then be calculated for the redundancy distribution in Figure 3 and a given estimate of the available bandwidths, B_j, $j = \{1, 2, 3\}$.

3.3. Example with Redundancy

When redundancy is present in the description set, the expressions for $P(Z_i)$ become slightly more complicated. An example of such a distribution is given in Figure 4.

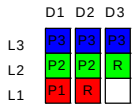

Figure 4. Example of descriptions requested with redundancy.

Using the general rule $P(Z_i)$ $i = \{0, 1, 2, 3\}$ equals the following.

$$\begin{aligned}
P(Z_0) =& (1 - P(D_1))(1 - P(D_2)) \\
P(Z_1) =& P(D_1)(1 - P(D_2))(1 - P(D_3)) \\
&+ (1 - P(D_1))P(D_2)(1 - P(D_3)) \\
P(Z_2) =& P(D_1)P(D_2)(1 - P(D_3)) \\
&+ P(D_1)(1 - P(D_2))P(D_3) \\
&+ (1 - P(D_1))P(D_2)P(D_3) \\
P(Z_3) =& P(D_1)P(D_2)P(D_3)
\end{aligned} \tag{4}$$

Given these distortion probabilities and using equation (1), the expected distortion can be calculated. The objective is to perform these calculations for every redundancy distribution and select the one yielding the lowest expected distortion.

4. NUMERICAL RESULTS

In this section the potential of a scheme utilizing the concept of MDC-CC is investigated. Consider a scenario with three descriptions and three nodes, as illustrated in Figure 5. Each node receives a full description from a source and must distribute this description to the other nodes according to their request.

The distortion can be calculated using the rate distortion function given in equation (5). This function has been estimated from the applied H.264 codec.

$$D(R) = e^{4.5792 - 0.00011028 \cdot R} \tag{5}$$

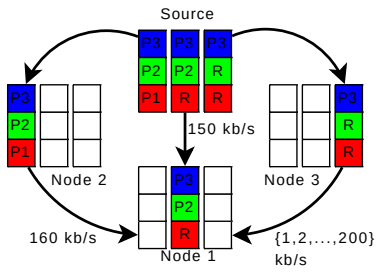

Figure 5. Scenario with three nodes and three descriptions where node 1 requests data from 2 and 3.

Any received fraction of the total media size can be interpreted as the same fraction of the source encoding rate. We focus on one of the nodes, node 1, and calculate the expected distortion for the eight possible distributions of redundancy. It is assumed that the available bandwidth estimator has a variance of 20 kb/s. The estimated bandwidth of the links carrying D_1 and D_2 are fixed at 150 kb/s and 160 kb/s respectively, while the estimated bandwidth on the link carrying D_3 is increased from 1 kb/s to 200 kb/s in steps of 1 kb/s. Each description has the size 13 kb, 45 kb or 141 kb when containing 1, 2 or 3 cells respectively. For each step the expected distortion at node 1 is calculated. This distortion is plotted in Figure 6 for all eight redundancy distributions as a function of the estimated bandwidth.

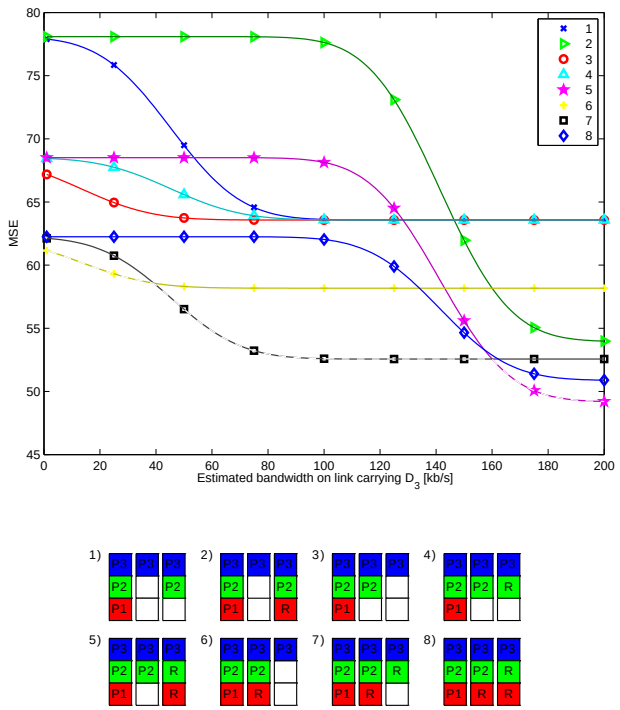

Figure 6. The expected distortion calculated for eight different distributions of redundancy as a function of the bandwidth on the link carrying D_3.

As the estimated bandwidth increases different distributions of redundancy yield the lowest distortion. By calculating the expected distortion a node can request the distribution of redundancy that results in the lowest distortion. In the case illustrated in Figure 6, node 1 would select distribution 6, then 7 and finally 5, as showed by the dotted part of the graphs.

Note that curve 8 in the figure is regular MDC, since no redundancy has been removed. Curve 1 and 3 are equivalent to LC, because no redundancy is left. Figure 6 shows that the expected distortion can be significantly reduced compared to MDC and LC, in this particular scenario, if redundancy levels are changed dynamically. An improvement in MSE of up to 9.5 is achieved over MDC, and up to 11 over the best performing variant of LC.

5. CONCLUSION

A scheme based on the concept of Multiple Description Coding with Conditional Compression (MDC-CC) has been presented. The idea is to combine the virtues of MDC and LC. MDC-CC is particularly suitable for cooperative distribution of multimedia content in cases where the downlink/uplink capacities of the terminal nodes are highly asymmetric. This is typically the case in real scenarios where link bandwidths often vary randomly. Under the assumption that an estimate of the instantaneous bandwidth is available, the scheme is able to select the amount of redundancy that results in the lowest expected distortion. Performance estimates show that in the given scenario the proposed scheme achieves a significantly lower distortion than both MDC and LC, which indicates that the concept of MDC-CC holds a great potential.

6. REFERENCES

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