A Peer-to-Peer Network Architecture for Distributed Video-on-Demand Appliances in Enterprise Networks

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Abstract
Video-on-Demand (VoD) applications have attracted a lot of attention recently and increasingly become a competitive factor on commercial consumer markets. Traditionally, these appliances rely on a client-server architecture where a single server or a cluster of servers stores content that is on request transmitted to the demanding client. VoD servers are expensive and significantly increase the purchase costs as they must be powerful and own high storage capacities. Furthermore, they usually exhibit high capacity network links as in worst-case scenarios hundreds and more of data-intensive video streams must be sent out simultaneously. Consequently, this link often becomes the bottleneck of the system, thereby decreasing the Quality of Service (QoS). Peer-to-Peer (P2P) networks are a popular Internet community-driven approach that may overcome these major drawbacks and additionally help to balance workloads across network links with the benefit of higher data-rate throughput and increased reliability. This paper presents a new QoS-oriented architecture for VoD systems in enterprise networks. It contrasts to other solutions, it exploits P2P approaches and thus significantly reduces purchase costs and overcomes the traditional drawback of client-server based solutions. It uses true point-to-point communication in order to preserve the On-Demand character of respective applications rather than building multicast communication trees that are widely addressed in comparable solutions. We furthermore propose P2P data replication strategies to ensure high content availability and innovative workload scaling to avoid local bottlenecks and hence enhance QoS. Moreover, we exploit the MPEG-4 video compression standard and develop a protocol for scalable video content delivery across distributed networks and end-devices, thus enhancing the QoS.

Keywords: Peer-to-Peer Networks, Quality of Service, Video-on-Demand, MPEG-4, Content Replication

1 Motivation
Premium multimedia services like Video-on-Demand (VoD) have become a major competitive factor for consumer markets recently. Internet content providers offer video downloading and video streaming opportunities, transport companies equip vessels with high sophisticated Info- and Entertainment systems and mobile service providers are striving for adaptive video content delivery with the forthcoming UMTS standard.

The success of these applications in enterprise networks strongly depends on the Quality of Service (QoS) [1] delivered to the customer. Superior image quality at frame-per-second rates conforming to the PAL or NTSC standards and bounded end-to-end delays are required to make VoD an entertainment event. Improved reliability in terms of highly available video content in fault-tolerant systems can be expected to further push these applications in case these features can be provided at affordable prices. From the service provider's point of view, scalable video content delivery is required to transmit the same video content to heterogeneous networks and devices commonly found in the home and mobile networking domains. The QoS needs to be adjusted accordingly.

Traditionally, VoD follows a client-server approach. Video data is stored on a centralized server and streamed to the demanding clients. These approaches exhibit significant drawbacks compared to distributed approaches: Servers represent single points of failures that may decrease the reliability of the system and hence the QoS delivered to the customer. Furthermore, they require high capacity network links as multiple streams may be sent out simultaneously. Still, the last mile to the server often causes bottlenecks and network congestions.

Similarly, a processing unit with high computational power to continuously fill the network pipes is required. The high demand for network and processing power resources increases the purchase costs of these systems dramatically that hence mostly become unaffordable.

Further, converging trends make interoperable applications convulsively cross the LAN border [2], VoD peers may be distributed across heterogeneous networks and end-devices that feature limited bandwidth and resource restricted processing power. As a consequence, the quality of the video content needs to be adapted accordingly and QoS support is required from the source to the sink.

Imagine a scenario where a network content provider streams the same MPEG video content to two different end-clients: A state-of-the-art desktop PC connected through Digital Subscriber Line (DSL) to the Internet and a cellular phone connected through UMTS. Whereas DSL currently features data rates of up to 1.5 Mbit/sec, UMTS expects typical real life data rates of 144 kbits/sec. It is obvious that the QoS of video delivery needs to be adjusted accordingly.

This paper presents a new Peer-to-Peer (P2P) Video-on-Demand architecture for autonomous enterprise networks (e.g. universities, hotels, hospitals) as a promising approach to overcome these major drawbacks. We consider enterprise networks as networks that feature independent subnets interconnected by routers. Instead of multicast communication trees that are widely addressed by other approaches, we consider true point-to-point communication in order to preserve the On-Demand character of respective applications. Further, content segmentation shall be avoided. Though the idea of P2P is not new, it has rarely been combined with VoD applications and QoS ap-
proaches in enterprise networks to form a cost-effective, highly scalable and QoS supported architectural solution.

We exploit the advantages of P2P approaches and avoid global computational bottlenecks by replacing the central server by peers that simultaneously act as client and server. Hence, the network load is equally distributed across all network links in case an appropriate content storage strategy is applied. Such a replication strategy which ensures that highly frequented content is distributed across the network is also presented. It avoids single points of failures and increases the content availability, and thus the reliability of the system.

In order to ensure real-time content delivery, the proposed VoD architecture is combined with the Intserv [3] and Diffserv approach [4] that allow to reserve bandwidth on dedicated network paths and support class-based traffic flows, respectively. Further, we propose to deploy Multiprotocol Label Switching (MPLS) [5]. MPLS is a standard-approved approach that aims to avoid hotspots through enhanced traffic engineering. The Rendezvous Server hereby continuously tracks available network bandwidth and peer resources and determines the network path with the highest resources at disposal for video delivery, thereby contributing to prevent single hotspots. It also acts as a directory service that allows peers to locate one another.

Furthermore, this paper introduces a method for scalable video content delivery across heterogeneous networks and end-devices. It exploits the improved scalability features in MPEG-4 and encodes and transmits video content with a quality that is strongly related to the currently available bandwidth and processing power at the end-client. Thus, the bandwidth requirements for video streaming can be adjusted with respect to the available resources of the peer allowing to adapt the QoS.

The rest of this paper is organized as follows: Section 2 gives a short introduction on Peer-to-Peer networking and video compression and Section 3 summarizes related work. Section 4 describes new innovative methods for P2P content replication and workload scaling. Section 5 addresses adaptive network and end-device specific content delivery though MPEG-4. A summary is given in Section 6.

2 Introduction to Peer-to-Peer Networks and MPEG-4

Peer-to-Peer Networks P2P networks have gained a lot of popularity within the last two years. Peers offer computing or storage capacity to others while consuming from other peers at the same time. Consequently, a peer simultaneously acts as a client and a server. The popularity of P2P applications can be traced back to filesharing and Instant-Messaging applications (e.g. Napster, eDonkey, Gnutella, ICQ, MSN-Messanger, etc.).

The architectural idea for P2P networks is not new and already came up at the beginning of the internet age. However, as central services were continuously developed this architecture became less important. Up to the last few years the architectures within the Internet exhibited classical client-server structures. Client-server based applications include mail-server (SMTP, IMAP, POP), web-server (HTTP), FTP-server, LDAP-server, etc. The major drawback of these architectures is the generation of bottlenecks.

In order to offer peers the possibility to contact each other so called Rendezvous Servers (RS) are often used. These servers that are similar to a directory service only know several peers and store references of content and services peers. To avoid scaling problems there are several RSs within a network that interact with each other in case of lookup queries they cannot serve. Peers that announce themselves to a RS are within the RS’s Realm. Alternatively it is also possible to use P2P Indexing services without any kind of RS, e.g. like CAN [6], Chord [7] or Pastry.

Introduction to MPEG-4 The MPEG standards developed by the Motion Pictures Experts Group have grown to become world-wide standards for video compression. They reduce the workload on processors and networks by exploiting the intrinsic redundancy between consecutive video pictures. MPEG-4 in particular covers a wide area of bit-rates ranging from below 64 kbit/sec for applications with extremely low bandwidth up to 4 Mbit/sec for video streaming applications [23]. It originally targeted at video streaming applications used in environments with very restrictive bandwidth at disposal, e.g. cellular phones [8]. However, as the allocated encoding bit-rate in MPEG-4 is not fixed, it can be even further increased. It is therefore a promising approach for adaptive video content delivery.

In contrast to its predecessors [9], MPEG-4 allows to decompose video scenes into single natural or synthetic audio-visual objects that are separately encoded and transmitted over the network to the client through so called Elementary Streams. Examples for these objects range from primitive media objects like audio or still images to complex object representation in 3D environments. The improved spatial and temporal scalability thereby allows to send base information of an audio-visual object required for a minimum QoS in a base Elementary Stream, and further information improving the stream resolution or fps-rate in additional enhanced Elementary Streams.

In order to exploit the redundancy in video streams, MPEG-4 defines three particular types of Video Object Planes (VOP) that represent temporal instances of an audio-visual object. These VoPs exhibit different compression ratios and are referred to as I(intrapicture)-VOPs, P(predicted picture)-VOPs and B(directional predicted picture)-VOPs. I-VOPs serve as reference VoPs to P-and B-VOPs whereas P-VOPs are predicted VoPs that collect relevant information encoded in former I-VOPs. They also serve as reference VoPs to B-VOPs. Consequently, I-Vops and P-VOPs are also referred to as reference VoPs. B-VOPs can be either forward or backward predicted and likewise exploit redundant information encoded in previous or subsequent VOPs. The decoding times of back-to-back VOPs can thereby vary by factor of five or even more. Furthermore, I-VOPs usually consume the most processing time for decoding, followed by P-VOPs and B-VOPs [10].

Besides these scalability features that allow gracefully adjustable video quality with regard to network capacity, the major benefits of MPEG-4 are fast encoding mechanisms, reusability of video objects across different video scenes and platforms, and QoS support for network service providers.

The core between the application and the transport layer is provided by the MPEG-4 Delivery Multimedia Integration Framework (DMIF) that abstracts video transmission from the underlying media. Currently, the standard supports homogeneous network protocols like IP, ATM, mobile, PST-Nand, Narrowband, ISDN. As the standard represents an open platform further protocols can be integrated. Moreover, it presents an API to the communication model that supports
continuous QoS monitoring. The integration of QoS models is, however, left to the developer.

3 Related Work

Gelman et al. present [11] an store-and-forward architecture that can provide VoD. Their architecture consists of four basic elements: The Information Provider warehouse stores video material and transmits it through high speed ATM network links to the central office that provides a processor responsible for service management and video buffering. Several such central offices exist in the architecture, thus allowing each client to address the nearest office in order to achieve a better data throughput on a best-effort strategy. On request, the central office connects directly to the network customer and the customer premise equipment.

Gelman et al. claim their approach to be real-time capable, providing network connections faster than required for video delivery at about 1.5 Mbits/sec. However, the bandwidth is not guaranteed, significantly decreasing the QoS in case of network congestion. Furthermore, they use a distributed client-server based approach that exhibits all the traditional drawbacks in terms of cost effectiveness and reliability. This paper presents an an architecture that exploits Intserv and Diffserv approaches for bandwidth reservation, hence increasing the delivered QoS. Moreover, we use a self-configuring P2P architecture with intelligent content replication that improves the reliability and the scalability of the VoD system.

Balmer et al. [12] introduced a QoS negotiation protocol for a Diffserv-oriented video streaming Multicast architecture. Hence, a client addresses its local QoS broker within its Internet Service Providers domain for QoS parameters negotiation, e.g. video stream quality and time of transmission. On behalf of the client, the QoS broker negotiates for Service Level Agreements with QoS brokers from other domains the video delivery data path comes across from the Content Provider. It then uses the Diffserv approach for reserving bandwidth along the respective network path.

Similar to the first approach, Balmer et. al. present a client-server based approach that requires high sophisticated video servers with high capacity network links. Furthermore, a Service Level Agreement will be hard to find if video streams must be transmitted through various domains. P2P networks allow to significantly reduce the hardware requirements of the video servers and balance the workload over all participating peers. Furthermore, intelligent content replication strategies as presented in this paper ensure that the video content is available within the demanding clients neighborhood, thus easing QoS negotiations.

Burchard and Lueling [13] describe an architecture for a scalable server management system that is capable of managing media assets stored on large-scale media server networks. They propose an easy to handle management software that organizes the media server network such as one or more servers are used as content caches. The content replication occurs on knowledge about clients preferences, e.g. content categories and user profiles. In order to provide sufficient bandwidth for streaming and non-streaming traffic they assume Diffserv-enabled hardware.

Burchard and Lueling also use a client-server architecture where clients connect to dedicated media servers in order to obtain content. The advantages of P2P solutions over these traditional approaches have been discussed before. Moreover, content replication occurs on a priori knowledge about user behavior and content categories. In our approach, we choose a method that is capable of modelling seasonal timeseries that can be made to achieve a appraisal for future values, thus enhancing the replication strategy.

Lately, new P2P streaming approaches have emerged [14] [15] [16] that establish an efficient multicast tree where each peer relays the incoming stream to a subtree-node. Furthermore, there are also P2P architectures that consider the "many-to-one" streaming and concentrate on efficient data segmentation. However, these approaches build on different foundations. The solution suggested in this paper presumes the "On-Demand" character and hence only establishes point-to-point communication instead of multicast. Furthermore, this paper considers autonomous enterprise systems for companies, universities or hotels and hence may exploit the Resource Reservation Protocol (RSVP) [3] upon the IGP routing protocol which ensures bandwidth reservation and fluent view (MPLS is also possible). Also, we do not partition the movie content. However, the serving peer may change if the Admission Control signals sparse resources.

4 Intelligent content replications mechanisms for Peer-to-Peer Enterprise networks

Most traditional VoD applications rely on a client-server architecture where the video content is stored on a single server or a cluster of servers. The video is then on request streamed or transmitted to the client. These servers usually require tremendous network and processing resources in order to serve multiple clients requests simultaneously. Still, the last mile to the server often becomes the bottleneck of the system because all clients are served by this one central network link. The QoS delivery of video streams cannot be guaranteed in case the bandwidth requirements exceed the resources at disposal. In order to overcome this major drawback network workloads need to be distributed and scaled as it is often achieved in P2P networks. Applying these techniques to VoD applications allows each peer in the network to act as a restricted video-server by offering a low number of selected movies to all other peers. As a consequence the workload is distributed among all participating peers.

The architecture of such a video-P2P enterprise network realized in a LAN is shown in Fig.1 where several peers in a network are connected to a Layer2-Switch. Each peer contains a P2P middleware which ensures the basic communication and interoperability with other peers and in particular with the rendezvous server for content reference exchange. Several sub-networks are interconnected through routers. The Quality of Service support is provided by the IntServ and the MPLS approach. Intserv defines a set of extensions to the traditional best effort model of the Internet with the goal of allowing end-to-end QoS to be provided to applications. The Resource Reservation Protocol (RSVP) [3] represents an implementation of the IntServ idea that determines a fixed path for a video stream in the network and reserves the necessary bandwidth. MPLS on the other hand is a standardized approach that allows routers to redirect packets along specified routes in accordance with the negotiated QoS. The Label Switch Path (LSP) denotes the route along which packets are forwarded. It qualifies for load balancing by re-routing packets around network hotspots. RSVP has been extended recently to reserve
bandwidth across established LSPs [17]. In order to prevent over-reservation of resources an Admission Control for RSVP is processed [18]. Likewise, the aberration from the average latency (Jitter) may be considered as bounded.

The RS primarily stores references for video-content within its own Realm. References with other realms are exchanged for adjustment purposes only. In case the RS fails during execution, all peers in the realm vote for a new RS among the active peers to take over.

The distribution of the redundant movie-content results in a distributed optimization problem where we distinguish between two techniques:

- **Proactive acting**: Copy content with IP Best-Effort technique.
- **Streaming with guaranteed Quality of Service** through extended RSVP and MPLS

The RS does not exclusively act as directory service for its own realm but rather acts on its own. This means a proactive load-management is performed after information exchange with other RSs. Video content that is accessed more frequently in other realms but is unavailable in the own realm is copied to a peer inside the own realm (via best-effort). The replication strategy is founded on methods for modelling stochastic processes/timeseries like the Autoregressive Moving-Average (ARMA) processes by Box and Jenkins [19] or an extension to this approach, the Seasonal Autoregressive Integrated Moving Average (SARIMA) processes. Both contributions are capable of modeling seasonal timeseries that can be made to achieve an appraisal for future values [20],[21]. Furthermore, SARIMA can be combined with the time-dependent access frequency for individual video content. Thus, we achieve an advanced caching strategy because videos can be replicated before queries are sent to the RS.

Additionally, movies that are streamed into the own realm and which have been unavailable before are kept as local copies. If the storage capacity in a realm is exceeded, different exclusion strategies must be considered. The strategy relies on the principle of reference locality - data that has just been used is assumed to be accessed again in the near future - which is exploited in many caching strategies like Least Recently Used.

In order to avoid that video-content is ousted out of the whole network a classification of content is necessary. This allows the optimization strategies to determine which content may be ousted. Thus, it is guaranteed that at least one copy remains available in the whole network. Further optimization strategies have to take drop-out probability, device constraints (e.g. PDAs, Mobile Phones) and bandwidth constrains into account. This is necessary as the streaming-source may be changed at runtime when Admission Control on the realms’ RS detects another source with significantly higher resource efficiency.

Besides ensuring content availability and replication, the RS also addresses the need of spanning network workload balancing in order to avoid hotspots, i.e. highly frequented network links, that may create congestion and thereby decrease the system performance. Mainly two reasons are responsible for hotspot emergence in a P2P architecture as shown in Fig.1.

Video content is only sparsely available but increasingly demanded from peers. Consequently, a small amount of peers that hold the content (source peers) may have to serve a vast number of content enquiries from demanding peers (destination peers), possibly resulting in network congestion on particular links. This issue can be addressed by appropriate content replication strategies.

On the other hand, the RS can also contribute to avoid hotspots by tracing workload on the participating peers and connecting network links (see Fig.2). In case a destination peer issues a content query to the RS (1), the latter checks all source peers that hold the respective content for their current workload, in this case Client C in Subnet 1 and Client B in Subnet 2 (4). Source peers that reside in other realms are contacted through the respective RS. The RS furthermore determines the available bandwidth all along the path to the source peers by sending MPLS RSVP Path messages (2). Each node that supports RSVP records this message and forwards it to the router of the peers subnet. In case the peers accept the communication request, they respond to the message by transmitting an RSVP Reservation message (RESV) the reverse path the PATH message used. Each router makes the corresponding reservation and forwards the message upstream. On Response (3), the RS selects the most appropriate source peer according to a tradeoff decision between available bandwidth and processing power (in this example Client C in Subnet 1), reserves the bandwidth on the path, and delivers the content reference back to the destination client (5). Furthermore, the RS cancels the bandwidth reservations along the paths to other peers (6). The destination client that may then address the source peer for content delivery (7).
5 QoS adaptation for video content delivery in distributed networks and end-devices

The RS acts as a directory service for other peers in the realm and controls the QoS for inter- and intra-realm communication according to current processing workloads and available bandwidth. However, in case the encoded video content requires more bandwidth than available for transmission, or the destination peer (currently) exhibits low processing resources, the source peers request usually must be rejected as the QoS cannot be guaranteed in these conditions [22]. On the other hand, some devices may not even be able to display videos with high definition TV resolution as it may be provided by some peers, and consequently significant bandwidth is wasted. An appropriate solution that may overcome this drawback is to scale the video content in terms of fps-rate and picture resolution with respect to network- and processing power capacity. Scalability is a supported feature in the MPEG-4 video compression standard [23]

Consider for example an accessible P2P network in the home, office and public environment (see Fig.3, Realm A) that provides connected devices with the possibility to request content from a Service Access Point (SAP) that connects to a RS. The RS on the other hand is connected to other RSs that all feature DiffServ support [4] in order to guarantee network spanning QoS. A framework for integrated service operation over DiffServ networks has been proposed in [24]. The devices (e.g. PDAs, Celluar Phones, Notebooks) connect to the SAP through wireless communication, e.g. Bluetooth or WLAN. We refer to this network as a Bluepac Area Network [25]. Obviously, the video content needs to be compressed in such a manner that it fits the currently available bandwidth (e.g. a maximum of 2 Mbit/sec per cell for forthcoming Bluetooth technology or 54 Mbit/sec per cell for 802.11a or 802.11g) and the processing power of the end-devices that is required to decode the compressed information. The latter is all the more important if embedded devices that usually exhibit limited processing resources are addressed, e.g. cellular phones.

The MPEG-4 standard provides such means in terms of spatial and temporal resolution that enable service providers to stream the video with a reduced frame-per-second rate or a decreased resolution, respectively without having to re-encode the video. This is achieved by following a layered approach where the base layer encodes the basic quality and upper layers further enhance the quality. Consequently, devices and networks with restrictive resources for example shall only receive base layer quality, where enhanced quality can be delivered to other devices. In order to exploit these scalability features in MPEG-4, a network and device-spanning service-contract needs to be developed that allows to exploit the available resources most efficiently. The contract is negotiated among the RSs that share knowledge about their realms and their connected devices. Parts of this contract are already addressed in Section 4. The following example extends this contract negotiation:

Assume a device in Realm A issues a content request to the RS (1). The RS determines the source peers that hold the content, determines the available bandwidth along the network work path and finally selects a client in Realm C as the source peer that delivers the desired content on a tradeoff between bandwidth and available processing resources. It additionally reserves the required bandwidth (see Section 4). On forwarding the content request, the RS in realm 1 also wraps device network specific information like processing power and available network resources in its own realm (2). The RS in realm 3 analyzes these additional information and adapts the content quality accordingly (3). We assume that content is stored in high quality and the quality needs to be decreased in order to lower the resource requirements. The RS may consider the following options:

- Reduce the fps-rate or picture resolution by exploiting improved MPEG-4 scalability features like temporal and spatial scalability. Consequently, only the required picture layers are transmitted. Thus, the required bandwidth as well as the necessary processing power at the end-device for decoding the information is reduced.
- Increase the compression ratio by convulsively using B-VOPs. B-VOPs exhibit higher compression ratios than other VOPs due to bidirectional predictive encoding and decrease bandwidth and processing power requirements. On the contrary, the quality of the encoded picture is diminished. This methods requires to transcode the video content.
Adjust compression algorithms. Highly compressed video usually requires less bandwidth at the expenses of additional decoding efforts. On the other hand, lowering the compression results in more data, but also reduces the processing time for decoding. This methods also requires to transcoded the video content.

Note that in the last two cases the video content needs be transcoded in order to adjust the quality. This task is usually done by the RS as it usually exhibits the highest processing power. The RS may now select the respective video content quality with respect to the destination peers constrains.

- low bandwidth/low processing power: The video is transmitted with reduced fps-rate and/or reduced resolution and increased compression ratio in order to reduce bandwidth, thereby decreasing the video quality. The compression algorithm is adapted such as it fits the maximum available bandwidth rate in order to reduce processing power for decompression.
- high bandwidth/low processing-power: The compression algorithm is adjusted such as it fits the maximum processing resources at disposal at the destination client in order to reduce resources required for decompression.
- low bandwidth/high processing-power: The video is transmitted with low fps-rate and the compression ratio is increased to reduce bandwidth requirements.
- high bandwidth/high processing power: Transmit video with optimal quality.

The source peer now streams the adapted video content to the destination peer along the reserved network path (4). However, continuous media processing like MPEG-4 video streaming tends to vary significantly in its request for decoding system resources which causes the CPU workload on resource restricted devices like PDAs to change dramatically. Consequently, an Admission Control that is built on an accurate Worst Case Execution Analysis [26] for MPEG-4 decoding is required. The Admission Control determines the impending resource requirements on the destination peer in advance and delivers feedback to the RS in case the available resources are not sufficient. As a result, the contract between the RSs continuously needs to be re-negotiated and the video quality must be re-adjusted. Real-time CPU scheduling is further required to adapt to the frequently varying workloads. A method for real-time scheduling of MPEG-2 streams and a corresponding Admission Control that is also applicable to MPEG-4 has been in introduced in [22].

6 Summary

This paper introduced a new approach for exploiting Peer-to-Peer networks for Video-on-Demand applications in enterprise networks, thereby guaranteeing end-to-end Quality of Service support based on common network (Intserv, Diffserv) and client (real-time scheduling) QoS methods. It presented a P2P architecture that particularity addresses research aspects for innovative content replication and network scalability to avoid the emergence of hotspots. Furthermore, MPEG-4 was identified as a promising video compression standard that serves the needs for adaptive video content delivery. This contribution exploited the improved scalability features and presented an architecture and protocol that allows to transmit encoded video content irrespective of the end-devices processing power and network connection.

In future, this approach will be implemented and integrated in a distributed Peer-to-Peer network where some peers act as a digital VCR to obtain real-world evaluation results and demonstrate the superiority of the new approach (available for final paper). In order to follow the network spanning idea of the approach, the video content will be delivered to resource restricted clients using wireless communication.

References


