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Peer-to-Peer Time-shifted Streaming Systems

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Abstract

In live streaming systems (IPTV, life-stream services, etc.), an attractive service consists in allowing users to access past portions of the stream. This is called a time-shifted streaming system. In our vision, a centralized time-shifted streaming system face scalability and ethical issues, therefore, we address the problem of designing a peer-to-peer system where peers store and deliver past chunks. We first attempt to identify the main characteristics of time-shifted streaming system from well-known measurements of VoD and IPTV systems. These overlays are the first structures specifically designed for time-shifted streaming system. Although no evaluation is presented, these preliminary description aim to foster discussions on a critical service.

1 Introduction

Context. The omnipresence of live streams (i.e., streams that are continuously produced from fresh content) represents a challenging trend of the Internet. A tremendous scientific literature deals with live video streaming systems in the perspective that video streams will soon represent a large majority of the whole Internet traffic [1]. Still, other forms of live streams are emerging, in particular new forms of life-stream. The concept originally coined by Vannevar Bush [2] is currently revisited by popular social network tools like twitter: every user is a producer of a life-stream, a stream of personal data that is inherently made public in order to be consumed by friends. Should life-streams joint with multimedia data generated by passive life experience capturing systems [3], the traffic related with these life-stream applications could become huge. In parallel, the proliferation of sensors and the rise of the Internet of things are expected to generate also a large amount of data streams [4]. Without loss of generality, we assume in this paper live streams consisting of a continuous series of chunks that are generated by a producer (or source).

Problem. In most cases, these live streams are immediately consumed by some *clients*, the delivery at large scale being ensured by multicast protocols, powerful data-center or peer-to-peer exchanges. A critical service consists, however, in allowing clients to access *past portions* of a live stream. In the context of

IPTV, this is called the *time-shifted* television: clients start watching a TV program from the beginning although the live program has already started or been finished. This feature is currently offered by several public TV broadcasters on a part of their history, though these services will probably soon apply soon to the whole history, especially for life-streams and sensor-generated streams. Please note that the client may choose *any* past stream portion, the past portion is not restricted to the stream that the client may have previously downloaded.

We distinguish the stream producer, which continuously generates the content, and the stream provider, the entity responsible both to continuously store the whole stream in a persistent manner, and to serve clients issuing requests on past stream portion. A stream producer can rarely be a stream provider, e.g., when the producer is a set of tiny sensors or a frequently disconnected individual. Besides, a stream provider based on a centralized architecture admits some drawbacks. First, the upload bandwidth requirement is very high, because, contrarily to live streaming systems, time-shifted streaming systems can not directly use group communication techniques like multicast protocols or peer-to-peer systems, for the reason that clients require here distinct portions of the stream. Moreover, sensitive life-streams or personal sensor-generated streams highlight the ethical limitations of private data-centers: lesser privacy protection, data lock-in or third-party control. Therefore, in this paper, we address the design of a peer-to-peer provider for time-shifted streaming.

Related Works. The studies related to life-streams or sensor-generated streams have mainly assumed that stream producer and provider are the same entity. They focus on information retrieval techniques to improve search into stream history [3, 5]. Time-shifted video streaming has only recently been explored. Enhancements to streaming servers are proposed in [6]. The scalability issue of centralized architectures is temporarily tackled by the use of proxy caches in [7]. Cache replication and placement schemes are extensively studied by the authors of [8]. Finally, when several clients share the same Internet access, a patching technique described in [9] can be used to handle several concurrent requests on the same stream. A couple of preliminary works have sketched a peer-to-peer architecture for time-shifted TV systems. In [10], every client stores all downloaded video chunks. A Distributed Hash Table (DHT) is used to keep trace of the owner of every chunk, so that a peer able to upload a past video chunk can be found upon a simple request to the DHT. Similarly, a DHT is used to locate video chunks in [11]. Some additional proxies aim to ensure the continuity of video that are locally downloaded. These works appear to suffer from several crucial drawbacks. At first, the use of a DHT is actually irrelevant in this context. Indeed, two peers that are responsible of two consecutive chunks are not linked anyhow. Therefore, downloading a long portion of past video requires to send numerous consecutive requests to the peer-to-peer structure. Moreover, for every received chunk, a peer should notify the DHT, which is quite costly. Finally, the number of video replica is not guaranteed.

Contributions. This paper is made of two independent parts. First, we describe the main characteristics of time-shifted streaming with a specific focus on time-shifted IPTV systems. Unfortunately, no measurement on time-shifted

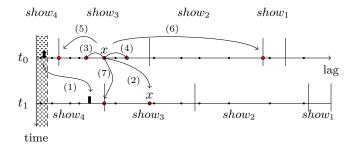


Figure 1: Use cases of time-shifted IPTV systems

IPTV have been published, so we composed from well-known characteristics of both live and Video-on-Demand streaming systems to conjecture the behavior of clients in time-shifted streaming systems. Second, we propose two peer-to-peer providers for time-shifted streaming systems. The first system is a structured system, namely turntable, that distributes on a set of network elements the task of the provider. That is, elements that are not client of the system can also participate to the storage, for example network operators may use some controlled set-top-boxes to raise a distributed time-shifted streaming system. The second one, namely interval overlay, uses exclusively the storage capacity of clients. The goal here is to ensure that all chunks are actually saved and available, while the cost is well distributed among clients.

2 Time-shifted IPTV Systems

The goal of this section is to characterize time-shifted streaming systems, *i.e.* describing the main use-cases, revealing typical client behaviors and popularity trends, and finally estimating the capacity requirements. We focus on peer-to-peer time-shifted IPTV systems because (*i*) IPTV systems have been extensively studied recently, so our conjectural analysis can base on proved existing facts, (*ii*) IPTV is currently the most attractive and challenging application.

2.1 Use Cases

Figure 1 depicts use cases of time-shifted IPTV systems. The y-axis represents the playing time of the video source, and the x-axis shows the time lag distribution of playing positions with the source at a particular time. The shaded area denotes the time range for the live streaming service, that is, peers in this area are synchronous with the source, but with a small time lag because of the buffer mechanism and network delay. The small black points denote the playing positions of peers in the system, and the rectangle with shadow presents a data chunk

In an idle context, peers and source are shifting with the same direction and

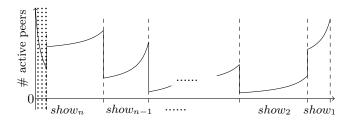


Figure 2: Population size vs. time lag (with shows)

a uniform velocity. So the time lags between peers and the source are constant from time t_0 to t_1 . From the viewpoint of chunks in case (1), chunks move along x-axis at the same speed as the source that continues outputting new content. Therefore, between time t_0 and time t_1 , a chunk moves $t_1 - t_0$ far from the stream producer. In television, the stream is basically cut into successive shows (news, movie, sport event, etc.). In this example, we represent four shows $(show_1, show_2, show_3)$ and $show_4$. From time t_0 to t_1 , the four shows move $t_1 - t_0$ far from the source.

We detail now the main events that are possible for a peer x in a time-shifting stream system. They are commonly referred to as VCR operations.

Pause: it occurs when a user leaves for a moment and is expected to resume streaming later from this current position. This is represented by case (2) in Figure 1. If the peer x performs a pause at time t_0 and continues playback at time t_1 , the lag between x and the source will increase by t_1-t_0 . This operation is implemented in current live streaming systems. In these systems, x continues to download the fresh content and buffers it.

Forward and Backward: a viewer in time-shifted IPTV system can perform forward or backward operations inside a show, as depicted in cases (3) and (4), or between different shows in cases (5) and (6). We distinguish these two scenarios because both starting and ending times of a show are special points where the behavior of clients can be very different from other stream positions.

Churn: a peer x may join the system as a live client, but it can also immediately start at a past position. As in other peer-to-peer systems, a peer should be assumed to be able to leave at any time, sometimes abruptly. We highlight however in the case (7) that it is also more probable that peer leaves at the end of a show, as it has been shown in recent studies [12].

2.2 Trends on User Behavior

To the best of our knowledge, no measurement study dealing with time-shifted IPTV systems has been published yet. However, we observe that this service combines somehow the real-time property of IPTV and the flexibility of VoD applications. Therefore we match the related characteristics of IPTV and VoD systems to highlight expected behavior of clients using a time-shifted IPTV systems. Note however that some of the ideas extracted from these well-known

measurements are in contradiction with the aforementioned previous works on peer-to-peer time-shifted video systems.

Stream Popularity: the relevance of Zipf distribution to describe the popularity of content in current large-scale applications has been widely demonstrated. It applies also to both IPTV [13] and VoD systems [14]. For time-shifted video streaming systems, it is reasonable to expect that streams will exhibit Zipfian popularity distribution. For very popular streams, the storage capacity can be neglected in comparison to the upload bandwidth requirement. In the opposite for the huge number of unpopular streams, the required storage can become the main problem. This differences may lead to distinct strategies.

Show Popularity: in the same manner, the popularity of different shows in a channel could be similar to VoD systems. Figure 2 represents a conjectured situation where the population varies with the popularity distribution of the shows in a channel. In [15], a peak has been identified at the beginning of each show. Then, as can be also stated in VoD systems, the number of watchers decreases, because a portion of viewers often surf the beginning of shows or leaves after few minutes. Note that the populations are probably different for distinct shows.

Churn: the spikes of departure have been shown to occur mostly either at the end of the show, or because the user does not find any interest after browsing the beginning of the show. That is, peers usually leave immediately, or simultaneously at the end of programs in [12]. Moreover, a large number of sessions end in the first minute, which means that these clients are not interested in the shows after browsing through the beginning. In this study, it is shown that more than half of the population quits during the first ten minutes of a show in average. Moreover, in most cases, the more popular is the show, the shorter is the session length.

2.3 System Perimeters

If we assume that the size of each chunk is 2 MBytes and the source video rate is 500 Kbps [16], the number of chunks that should be stored in one day is approximately 2, 700, so it represents more than 5 GBytes of video data. These numbers are respectively 80,000 and 160 GBytes for one month for only one stream. The amount of data that should be handled in time-shifted streaming system are several orders of magnitude larger than in VoD systems. That is, it is not surprising that many issues that can be easily tackled in VoD peer-to-peer systems can hardly find solutions in our context.

The approaches commonly used in peer-to-peer VoD systems to store data can be roughly classified into two categories: distributed data storage (e.g. [17]), and sliding window buffering (e.g. [18]).

In the distributed data storage, each peer is assigned to store some video chunks and serve other peers. Ideally, a peer is assigned to a small amount of chunks, therefore the impact of downloading them initially can be neglected, while it can not in time-shifted systems. Moreover, the total number of chunks

is fixed in VoD systems, although fresh chunks should continuously be treated in time-shifted streaming systems.

In the sliding window buffering, each peer caches the past downloaded chunks for a period of time before discarding them. It serves other peers with this cached content. This cache corresponds to a sliding buffer window with a fixed size, from the upcoming chunks that will be soon played to the chunks that have been played not so recently. In these systems, peers whose buffers overlap are likely to exchange data. However, in comparison to VoD systems where the typical video duration is not long, time-shifted streaming systems apply on far much longer time. Several issues immediately raise: how to ensure that a unpopular past portion of the stream is covered by at least one sliding buffer, how to dimension the buffer size, etc.

3 Our Proposals

Our purpose is to build a distributed time-shifted streaming system. We call peer an entity having both storage and network capabilities. We aim to utilize the upload bandwidth of peers to reduce the bandwidth burdens placed on the server. Among the peers, we distinguish the clients, who are also consuming the stream, and other elements that are generously contributing to the system without immediate reciprocity (for example, a set-top-box controlled by a network operator). We neglect here the selfish behavior of peers, that is, we do not design any incentive to prevent free-riders. Then, we say that a client can be either a live client (consuming the live stream) or a hookup client (consuming a past portion of the stream). The delivery of the live content (multicast, peer-to-peer, etc.) is out of the scope of this paper. Rather, we focus on serving the hookup clients. Please note that a VCR operation can make a live client become a hookup client, and vice versa.

We identify three main challenges in peer-to-peer time-shifted streaming systems: (i) how to store the continuous content output from the source; (ii) how to guarantee that every past chunk is still available in the system; (iii) how to retrieve a series of successive chunks from a past stream portion. We propose two possible approaches: a distributed turntable structure and an interval graph structure.

3.1 Distributed Turntable Structure

We propose first a structured system based on a turntable. See Figure 3 for a representation. The main idea is as follows. We divide the turntable into m sectors noted $s_i, 0 \le i < m$. Every peer joins a sector. The turntable implements a rotational motion in clockwise direction. At every time t, the producer, noted p, produces a new chunk that is sent to peers in a sector s_i , then the chunk produced at time t + 1 is sent to sector s_j with j = (i + 1) mod m, and so on. Hence, every new chunk is stored by a subset of peers. See

¹in the following, we omit the modulo for notation clarity.

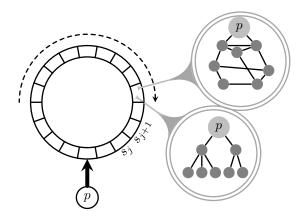


Figure 3: The distributed turntable structure

Table 1 to see a typical distribution of chunks to sectors. When a client wants to download any past portion of the stream, it should first determine the sector associated with the first chunk of this portion. After finding a peer that has stored the requested chunks in this sector, the peer can begin to download the stream. It should then jump to the next sector in order to retrieve the next chunk and continues consuming the stream.

Sector Id	Chunk Id			
0	0	m	2m	
1	1	m+1	2m + 1	
m-1	m-1	2m - 1	3m - 1	

Table 1: The chunk distribution in the turntable

The producer must be connected to at least one peer in every sector. These peers are called representant. When it is time for a sector s_i to download and store a chunk, the source alerts the representants for s_i and sends the chunk to them, then this chunk is diffused in the sector. The overall structure overlay formed by the turntable structure depends on how peers are linked inside a sector, which are called the $intra-sector\ links$, and how peers from one sector are linked to peers of the next sector, namely the $inter-sector\ links$.

The main purpose of the intra-sector links is to allow an efficient diffusion of fresh chunks into one sector. Moreover, the overlay formed by intra-sector links should also serve to implement a mechanism aiming to ensure a fair allocation of the past chunks. Indeed, past chunks concentrate on oldest peers, so oldest peers attract requests. This uneven request distribution may not reflect peer capacities (old peers may have a lower upload capacity than the new ones). Ideally, the number of replicas of a chunk should correspond to the number of requests emitted for the stream portion this chunk belongs to.

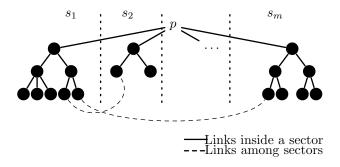


Figure 4: The tree-based overlay structure

The inter-sector links aim to ease the retrieval of consecutive chunks. A client x downloading a past stream portion will produce many successive requests to successive past chunks. The purpose of an inter-sector link is to connect two peers that are in successive sectors and that store some successive chunks from past stream portions. When x is served by a node $y_i \in s_i$, its next request will be in sector s_{i+1} , i.e. x should find in sector s_{i+1} a peer that stores the chunk next to the one it just downloads from y_i . Ideally, the peer $y_{i+1} \in s_{i+1}$ to which y_i is connected stores the next chunk that x will request, so y_i can introduce y_{i+1} to x and save request messages.

We describe in the following two possible implementations: a tree-based (see Figure 4) and a mesh-based (see Figure 5) overlays for every sector. Please note that, for clarity reasons, we do not give further implementation details, this is left for future works, especially a comprehensive system evaluation.

3.1.1 Tree-Based Turntable

The first proposal is to build, into every sector, a logical tree rooted on the producer, where the representants are immediate children and other peers self-organize to build a tree. In this configuration, the intra-sector links form m independent trees for m sectors. Thus, when representants receive a chunk from the producer, this chunk can be optimally diffused to all peers in the sector. Various optimization algorithms can be used in our context. In particular, algorithms for building minimum-cost spanning trees can help to diminish the network cost to span all peers (e.g., the number of Autonomous Systems (AS) traversed by a chunk in the tree). Another optimization consists in matching the capacity of peers (e.g., upload bandwidth) and their position in the tree (e.g., the level).

We propose also to implement a mechanism that allows every peer to know all the replicas that are currently stored in the sub-tree rooted on it. This can typically be implemented without much efforts with transmission of Bloom Filters where an entry i corresponds to whether the ith chunk is guaranteed to be found in at least one descendant. The purpose of this mechanism is twofold:

(i) if a chunk is missing at the highest levels of the tree, it is possible to run an emergency procedure aiming to reproduce new replicas of this chunk, (ii) when a peer receives a request for a chunk it does not have it can immediately know if the request should be routed to its children or its father. That is, a basic Bloom Filter mechanism may allow efficient replica management and request routing.

The drawbacks include that trees are known to be difficult to maintain in dynamic peer-to-peer systems, as other structured peer-to-peer systems. Moreover, the capacity of leaf peers is unused in the diffusion of live chunks, while the peers at the highest levels can be overloaded. Actually, a trade-off should be found between the number of leaves and the depth of a tree, which have a direct impact on the cost of the Bloom Filter mechanism and on the performances of the request routing. Finally, this structure is efficient to diffuse a chunk to all peers, but this may be unnecessary because only some replicas of fresh chunks should be stored.

3.1.2 Mesh-Based Turntable

The second proposal is to build, into every sector, a mesh-based overlay where the diffusion of chunks is based on gossip protocols. Every peer has a list of peers that it continuously refreshes. Peers exchange messages on a periodic manner, these messages may carry chunks or neighborhood information. The randomized processes in action in gossip protocol have proved to be both efficient and adequate to maintain consistently a given number of replicas in dynamic systems [19]. However, determining the adequate parameters for these systems, especially the frequency of message exchanges, is not easy.

In a mesh structure, a challenge consists in ensuring that every peer is close to any chunk, so that requests for past chunks can be treated as quickly as possible. We propose to use a mechanism based on domination theory. This mechanism is somehow similar as the one recently described in [20]. A set $D \subseteq V$ of vertices in a graph G = (V, E) is called a dominating set if every vertex x in V is either an element of D or is adjacent to an element of D. Most domination problems are NP-hard problems, so no exact solution can be computed in a reasonable time. In our case, a practical distributed solution aims to maximize the number of distinct chunks in the neighborhood. The idea is to build a domatic partition of the overlay, that is, to determine several distinct dominating sets, each dominating set being responsible to store a subset of the chunks of this sector. Every past chunk and every peer are associated with a color, the number of colors being the partition size. A peer in a color should be able to retrieve any chunk associated with this color. So, when a representant receives a new chunk, it sends this chunk to the neighbor that has the same color, then the diffusion is restricted to peers in this color. Similarly, when a request for a past chunk is received by a peer, it should first determine the color associated with this chunk, then forward the request to its appropriate neighbor.

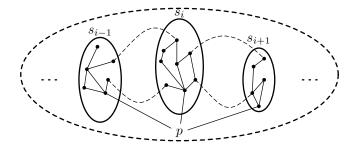


Figure 5: The mesh-based overlay structure

3.1.3 Discussion

The advantages of the turntable structure include that every sector should participate at the same level. Because every sector is associated with a chunk unit, the portion popularity variation does not impact the sector request load. Moreover, every sector should store the same amount of chunks. However, the cost of maintaining the structure in an efficient manner may be high. Moreover, it is not clear that easy incentive mechanism can be implemented in such a structure. Note however that, contrarily to previous works, the design of this structure fits definitely the characteristics of time-shifted streaming systems.

3.2 Interval Overlay Structure

We propose now an overlay structure based on *interval graphs*. Here, every peer is a client that is requesting a past portion of the stream. The idea is that the chunks sent to the clients are temporarily stored by the clients, so that other peers can request them.

First, we recall the definition of interval graph. A graph is called an *interval* graph if its vertices can be put in a one-to-one correspondence with a family F of intervals on the real line, such that two vertices are adjacent in G iff their corresponding intervals have nonempty intersection. Formally, let $\{I_1, I_2, ..., I_n\}$ be a set of intervals. A graph G = (V, E) is an interval graph when $\forall x, y \in V, \{x, y\} \in E \Leftrightarrow I_x \cap I_y \neq \emptyset$.

3.2.1 Description

In peer-to-peer VoD systems, each peer manages a sliding buffer containing some past chunks that have been already played and a few chunks that have been downloaded in advance. A sliding buffer is at a given time t an interval. We define, for every peer x, its interval I_x containing a left bound l_x , a playing position c_x and a left bound r_x . The value of these parameters are related with the source. That is, the interval $(l_x c_x)$ contains chunks that will be played (this interval may be incomplete, *i.e.* some chunks may be missing) and the interval (c_x, r_x) contains past chunks that have been played (it is expected to be full).

Peers connect with the other peers whose buffers overlap. We do not detail here the straightforward gossip protocol resulting eventually in that every peer is connected with all peers whose buffer overlap. As we previously noticed, the challenge of implementing such buffer-based techniques in time-shifted streaming systems is to ensure that all past chunks are in at least one sliding buffer. Our idea is that every peer should adjust its variable l_x and r_x , so that the global overlay respects some conditions. We formulate the problem as an optimization problem whose formulation is as follows.

Actually, the size of the buffers should be reduced. Indeed, the management of large buffers implies large neighborhood and potentially a large traffic. That is, our objective is to minimize the length of the intervals:

$$minimize \sum_{x \in V} l_x - r_x$$

The first constraint, obvious, is that the resulting interval graph should be connected. Furthermore, ensuring a sufficient redundancy requires a k-connectivity. In interval graphs, this notion is easier to understand, every chunk should be covered by at least k intervals. Formally:

$$\forall t \in [0, T], |\{x \in V : t \in (l_x, r_x)\}| \ge k$$

The second constraint is that peers have limited upload capacities. We denote by cap(x) the number of peers a peer x can serve. A peer y whose left interval (l_y, c_y) overlaps the right interval (c_x, r_x) is a neighbor that x will exclusively serve. If x accepts too many peers overlapping its right buffer, it will probably experience troubles in serving them. Therefore, we introduce the following constraint:

$$\forall x \in V, |\{y \in V : (l_y, c_y) \cap (c_x, r_x) \neq \emptyset\}| \leq cap(x)$$

It is easy to verify whether it is possible to build an interval graph respecting these constraints. Most algorithms for interval graphs are based on an iterative exploration of nodes based on their left (or right) interval bound. Here, we can use the playing time to iteratively explore the peers from the peers which is playing the freshest portion of the stream to the peers requesting the oldest stream portion. The k first peers should determine their left bound so that the graph is k-connected. Once these k first left bounds are set, every peer determines iteratively their right bounds so that the second constraint is not violated. Applying iteratively this process should determine a solution, if any. The optimal solution is not guaranteed, though.

The distributed implementation of this algorithm is also straightforward. A gossip protocol ensures that every peer is connected with a neighborhood that is beyond the set of peers to which it must be connected. Every event is diffused within this neighborhood. Every peer is continuously resetting its parameters by running the algorithm from the neighbor whose playing time is the closest to the source to the neighbor with the oldest playing position. When a peer

crashes or abruptly changes its parameters (e.g., after a VCR operation), the gossip protocol should ensure that a new neighbor is added, and the algorithm re-runs.

3.2.2 Discussion

The advantage of this interval-based overlay is that a peer should not download unnecessary chunks (or very few). Based on one-to-one relations, this overlay should also support well-known incentive mechanisms. The size of the buffer is not fixed, it depends on the popularity of the portion that is requested by the peer. In a very popular portion (beginning of a popular show), peers have a small buffer and interact with peers whose playing position is very close. On the contrary, peers enjoying a unpopular portion may have to manage a very large number of chunks. In a practical implementation, some dedicated servers may manage these unpopular portions. To the best of our knowledge, this is the first time that the management of buffer size aims to satisfy a large set of peers.

4 Conclusion

Time shifted streaming provides a new attractive service whose implementation is quite challgenging. We have raised two crucial drawbacks having the potential to prevent the use of data-centers: scalability and ethics. Although no measurement of current time-shifted services have been published yet, we propose a conjectural analysis highlighting the main characteristics of this service. Then, we describe two peer-to-peer systems: a turntable overlay and an interval overlay, both of them being still at the early stage of development. Future works include obviously a comprehensive evaluation of their performances.

Our feeling is that an early publication of the main principles of these overlays should foster fruitful discussions about the numerous issues that should still be tackled. In our opinion, previous works have only sketched unconvincing solutions. In this paper, the design of the proposed structures is expected to address some of the main problems (request of consecutive chunks, allocation of chunks, etc.), but we have emphasized that the management of both fresh and past chunks is still especially challenging.

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