Peer-to-Peer Netw. Appl. (2016) 9:1060–1073
DOI 10.1007/s12083-015-0388-1

Overlay construction for mobile peer-to-peer video broadcasting

Approaches and comparisons

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Received: 26 January 2013 / Accepted: 23 June 2015 / Published online: 10 July 2015

Abstract An efficient overlay is a crucial component of wireless cooperative live video streaming networks—an emerging wireless streaming solution with ever-increasing storage and computation capabilities, and provides scalability, autonomy, carrier-billing network bandwidth conservation, service coverage extension, etc. Based on whether routes are pre-calculated and maintained, or determined per-hop in reactive to each data piece, the streaming overlay can be classified as either unstructured, structured, or hybrid. We discuss issues, properties and example approaches of each category in detail, and present quantitative and qualitative comparisons on their strengths and weaknesses in terms of system robustness, overlay maintenance complexity, delivery ratio, end-to-end delay, etc. Finally we discuss some open issues and emerging areas regarding overlay construction.

Keywords Cooperative systems · Peer-to-peer computing · Multimedia communication · Wireless communication · Wireless networks

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1 Introduction

With the advances in multimedia capability of wireless devices, live video streaming to handheld devices has become a reality. Conventional streaming approaches utilize the client-server model, in which clients *pull* streams from the server via an access point (AP) or base station (BS). However such approach suffers from several limitations including heavy AP/BS load, high contention delay due to media access control and possible blind spots due to incomplete coverage. To overcome the above limitations, wireless peer-to-peer (P2P) streaming has been proposed. This is motivated by the much success of P2P streaming over the Internet [1]. In wireless P2P streaming, devices[1] form *an overlay network* and cooperatively exchange video data with each other to achieve cost-effective stream broadcasting. In wireless communication network (underlay), a *directional link* connects two nodes if the receiver is in the transmission range of the sender. An overlay in wireless multihop live video broadcasting consists of all the nodes and a subset of links, through which the video can reach all the nodes with certain objectives. This architecture is becoming possible by the fact that more and more wireless devices nowadays are equipped with multiple wireless interfaces (3G, Wi-Fi and Bluetooth) as well as antennas, and high memory and processing capabilities. Wireless P2P streaming is best suited for content of local significance, i.e., when a reasonably large number of clients in a local area are interested in the same video. An application scenario is that

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[1] In this survey we use users, nodes, peers, clients and devices interchangeably when referring to clients using mobile devices to receive the streaming.

users in an area such as a theater or a train try to view the same wireless video channel (news, sports, etc.).

Figure 1 shows the network considered for mobile P2P live streaming, where dashed lines indicate the underlay connectivities. There is at least one *source node* in the network who either generates video content, or gets it from the streaming server via AP using a *primary* channel such as 3G or 4G. The sources then share the data with their neighbors by means of short range direct connections such as Wi-Fi Direct or Bluetooth. The receiving nodes in turn share their content to their neighbors. Such cooperative video broadcasting overlay network is more scalable, can extend the coverage area, and can reduce streaming cost at each client.

To understand how different overlay designs can affect the wireless network performance, we need to first review the characteristics of wireless multihop network. Wireless multihop network bears the following distinctive characteristics:

- *Broadcast nature:* Each wireless transmission, whether unicast or not, will be overheard by others within the sender's transmission range. The broadcast nature brought several unique properties including high transmission efficiency, high loss recovery efficiency, high spatial diversity and loss recovery efficiency [24], per-hop media contention and potentially high interference/delay.
- *Scarce network resource:* Network resources in wireless environment, including mainly device computational power, network bandwidth and device energy, are often severely limited, and cannot afford the high control overhead as in wired P2P.

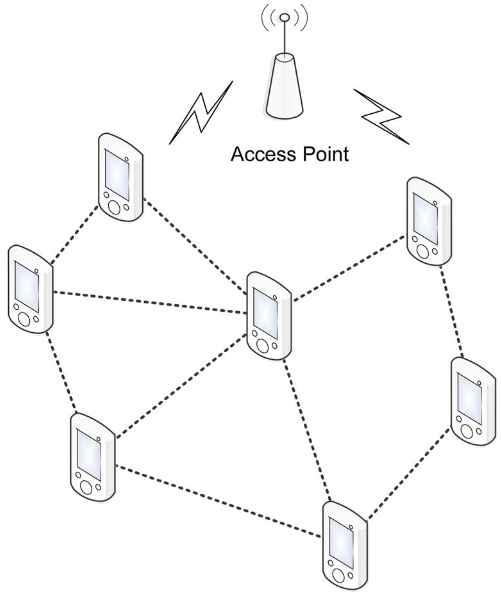

Fig. 1 Mobile peer-to-peer network in consideration

- *Limited "parent" candidates:* In wireless environment a client can only get supplied from one or a few neighboring nodes in wireless transmission range. So instead of the resource discovery problem faced in the Internet, Algorithms designed for wireless environment need to guarantee for each receiver, some of its reachable neighbors has both the requested data and sufficient bandwidth to serve it.
- *Different nature of loss:* Losses in wireless network are generally not caused by congestion as in wired network, but rather due to signal errors as a result of noise, interference or transient disconnection. In this case the congestion avoidance mechanisms such as the one used in TCP will only harm the effective throughput.

Due to these issues, existing *pull*-based cooperative streaming protocols that perform well in the Internet are no longer directly applicable to the wireless scenario, which requires a completely redesigned overlay network. An appropriately designed wireless overlay should generally exhibit the following properties:

- *Coverage:* Video broadcasting should cover all the receivers.
- *Path delay awareness:* Per-hop delay and the path length are the two factors contributing to path delay. Per-hop delay can be reduced by limiting regional traffic initiators, i.e., the density of relay nodes should be kept low. In order to avoid long paths, the overlay depth should be small, while the node degree can be increased to utilize the broadcast nature.
- *Loss control:* Appropriate level of redundancy can not only effectively and efficiently reduce loss, but may also increase packet diversity between neighboring nodes, to facilitate further cooperative loss recovery.
- *Energy awareness:* The total traffic, as well as per-node traffic should be kept low to conserve limited energy at each node. Low traffic density can also reduce media contention level and interference probability, thus reducing delay and increase transmission success rate.
- *Robust and Adaptive:* Node failure and mobility are inevitable in wireless environment. The overlay should therefore be adaptive to these changes without disrupting the live streaming service.

Inappropriately designed wireless overlay may easily cause excessive and unnecessary traffic, resulting in high media access contention and/or high interference (depending on whether collision avoidance (CA) is enabled), as well as fast energy drain. An optimized wireless overlay often achieves intended objective with small cost. For example, low energy cost (i.e., in terms of minimum network traffic) can be achieved while complying target residual loss rate requirement, or vice versa.

With the unique wireless network characteristics, and the importance of optimal overlay design, how to best construct the wireless overlay network to most utilize the overhearing feature, while reducing its negative effect becomes a vital problem. We witnessed that recent researches often focus more specific applications of live video streaming, while the wireless resource is simply assumed readily available for the sake of these objectives. However the importance and effect of designing an appropriate overlay network never become less vital. On the contrary, as newly proposed applications exploit and depend more on wireless network resources, overlay optimization becomes more and more necessary and beneficial.

In this paper, we survey major approaches of overlay construction for mobile P2P live streaming. In overlay construction, most studies often focus on objectives of either energy efficiency, normally in terms related to total network traffic incurred, or reliability (e.g., video quality), normally in terms related to residual loss rate experienced by mobile users. With different objectives, overlays generally fall into one of three major categories, namely unstructured, structured, and hybrid overlays, based on whether transmissions follow predetermined routes. This survey will focus on these three categories. Besides presenting these approaches in details, we also compare quantitatively and qualitatively their strengths and weaknesses. Through this discussion, we hope that one can better understand the challenges, design principles and research dimensions of overlay construction in wireless P2P live broadcasting.

Wireless P2P live streaming is an active research area. Apart from overlay optimization, many other issues have also been considered in literature for different network setups. Network coding can be applied in order to achieve higher transmission efficiency and/or error resilience [3, 6, 10, 25, 31, 33, 35, 37, 41]. Distortion-aware multipath streaming for multihomed clients is studied in [39]. Works in [26–28] study wireless transmission of free viewpoint videos. Cross-layer approaches have been proposed to utilize available information of different network layers and improve overall streaming performance [11, 12, 30, 32, 36]. Issues such as the security, effect of content popularity and client incentives are also important [8, 17, 20, 29]. Besides video streaming, another large body of work studies efficient file sharing that bears tolerance in delay and out-of-order arrival but requires 100% delivery guarantee [8, 13–15, 18]. Although the above areas are orthogonal to this survey, they are never the less important research directions that can help improve the effectiveness and applicability of wireless P2P live streaming.

As an alternative approach to achieve wireless live broadcasting, Multimedia Broadcast/Multicast Service (MBMS) may also be considered. As an orthogonal topic to P2P wireless video broadcasting, we will not discuss MBMS any further in this survey.

The remainder of this paper is organized as follows. In Section 2 we summarize the approaches, characteristics and challenges of unstructured overlay, followed by structured overlay construction in Section 3. Hybrid overlays are discussed in Section 4. We compare these approaches in Section 5. Open research directions are discussed in Section 6. We finally conclude in Section 7.

2 Unstructured overlay

The main characteristic of an unstructured overlay is that each hop of the routing of each data piece is determined independently on-the-fly at each intermediate node according to the network information at the time. There is no pre-calculated path maintained. Each node normally employs a distributed, gossip-like process to form a local overlay for each incoming data packet. There is no consistent global overlay as each node can tune its local overlay independently and on-the-fly according to local conditions during the streaming session. The motivation of such overlay is primarily its ability of dealing with network dynamics, as well as its simple implementation and distributed nature. Such unstructured overlay is robust to topology dynamics, and has been a great success in wired network for file distribution and video streaming, in which peers *pull* missing data from a set of other peers, and peer-to-peer paths form accordingly. However, naively applying this pull-based approach to mobile P2P environment would not lead to good performance due to the following reasons:

- *Formation of long path:* Without considering geographical distance among nodes, such pull operation may trigger the formation of long multi-hop wireless connections. With media contention, potential interference and even disconnection at each hop, this multihop path may result in high channel contention, high loss rate and unpredictable delay.
- *Broadcast nature unutilized:* This pull action fails to utilize the broadcast nature of wireless transmission, as multiple clients requesting the same content may pull from the same node, causing the node to serve each of them with a separate transmission. If the one-hop broadcast is enabled, the sender only need to transmit once and all its neighbors can overhear the transmission. We will see later that some work employ such *push* approach in their mesh-based video broadcasting in order to utilize one-hop broadcast.
- *Bottleneck:* The streaming server, the AP, or any client with multiple incoming requests may be overloaded with *pull* requests and the corresponding unicast-based

responses and become the bottleneck of the performance.

An efficient mesh-based mobile P2P live streaming protocol called **COSMOS** (Collaborative Streaming among Mobiles) has been proposed in [22]. COSMOS takes advantages of one-hop broadcasting and is based on *push* based operations instead of *pull* based P2P streaming techniques. It also utilizes multiple-description-coded (MDC) video structure to improve the robustness against peer churns. In COSMOS a small number of mobile peers are active pullers that request stream from the server, with the rest being passive receivers. A source node pulls a video description from the server via an AP and then broadcasts the pulled content to its neighbors using a secondary channel.

Peers periodically broadcast their *buffermaps*[2] to their direct neighbors. Based on the buffermaps received, a peer can determine the availability of a certain data piece among its neighbors. Upon receiving the data piece, it can then decides to rebroadcast if more than, say, 25 % of neighbors need the data, and suppress otherwise. A random delay reverse-proportional to such fraction is introduced prior to each rebroadcast so that a peer with more potential beneficiaries is always preferred to be the broadcaster.

COSMOS uses the above greedy approach to reduce relay overhead. The main issue however lies in the peer's local decision of whether or not to rebroadcast. As previously mentioned, the heuristic is the fraction of its 1-hop neighbors that could benefit from the rebroadcast. There are two possible consequences of this heuristic. First, some peers along the network boundary may be ”starved” as the number of beneficiaries at its sole upstream node is too low to trigger rebroadcast; Second, when the network is dense, even if a large number of a peer's neighbors could benefit from the rebroadcast, the fraction may still not be high enough to trigger the peer's rebroadcast. We refer to the above issues collectively as the “minority starvation” problem. To address this, COSMOS has a mechanism that, if a node has not received enough description within a certain period of time, it becomes a puller to get the stream from the AP directly. Another issue is the unpredictable performance brought by greedy approach. Although greedy approach is normally preferred because of its simplicity and the ability of approximating the optimal solution in many scenarios, it may not work well in certain topologies such as when choosing two or more relays with lower fraction values may collectively lead to a smaller total number of transmissions than choosing another single relay with the highest fraction.

In COSMOS,passive receivers are allowed to switch to pullers to ensure streaming quality. In COSMOS there is no explicit supplier-receiver relationship formed. Another approach to ensure streaming service availability is to allow nodes actively and explicitly choose their own stream suppliers from the neighbor set to form such relationship, instead of passively receives the stream. Nodes are then responsible to choose and update their stream suppliers, hence to reduce the probability of being starved.

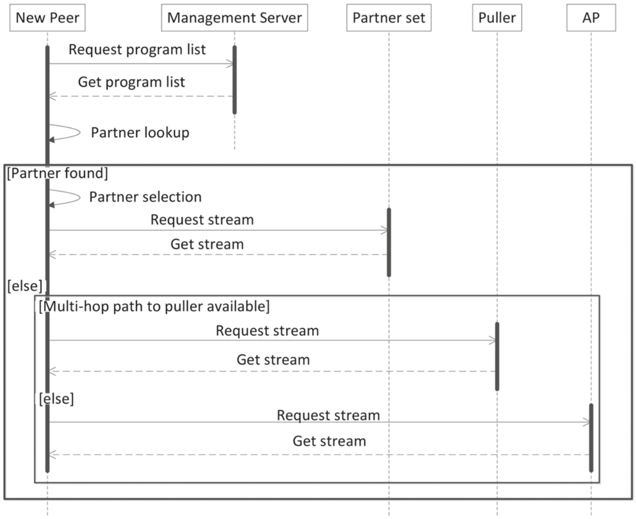

Fig. 2 The join process of P2PMLS

Discovering and selecting *partner set* (i.e., the set of supplying neighbors for a node) is proposed [16, 40]. Figure 2 shows the joining process of a new node in *P2PMLS* (P2P-leveraged mobile live streaming) [16]. A new joiner checks if there is any neighbor peer receiving the same stream through neighbors' periodical beacons. If such neighbors are found, a subset of them is chosen to be stream suppliers. The choice is made based on neighbors' remaining energy, mobility pattern and link condition.[3] If no such partner is discovered, then the node tries to find a supplier through a multi-hop path. If this again fails, then the peer becomes a puller itself. Their partner selection criteria tries to extend the connection lifetime. It however neglects the broadcast nature of wireless transmission. A possible scenario is that two nodes that could have been sharing a single supplier choose their own suppliers instead. The consequence is a increased number of unnecessary transmissions, as well as media contention and interference levels.

For better partner selection in case of mobility, the works in [40] introduces *preference score* of a neighbor node, which measures the mobility pattern similarity, as well as the load of the neighbor node. Let d_i be the distance between a node and its neighbor i, each with speed vector of V and V_i, and an angle difference of their speed θ_i. Further denote

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[2] Buffermap is a bit array with each bit corresponding to the availability of the data piece in the peer

[3] The detailed scheme in retrieving those parameters are not given, and we will see how mobility similarities are measured in another work later.

n_i as the current load of node i. The preference score is defined as

$$S_i = \frac{f \times \cos\theta_i}{d_i \times (n_i + 1) \times \sqrt{(|V| - |V_i|)^2 + 1}}.$$

Since overhearing is not assumed, a neighbor node is preferred to be a supplier if it is lightly loaded with a similar mobility pattern. Apart from the preference score, *tendency score* is also proposed to continuously measures the improvement of the preference score, so to quantify the "tendency" that each of the neighbors may become a good supplier candidate. All the neighbors are sorted first by preference score, then by tendency score, and top nodes with scores above the mean are chosen as suppliers. In case of insufficient supplier partners, instead of trying to establish and maintain a multi-hop path to a puller as proposed in P2PMLS, nodes are allowed to pull requested stream directly from AP.

More recently, Li et al. proposed a distributed scalable video (SVC) multicast algorithm that jointly optimizes video quality and network traffic [23]. Network coding is adapted within each layer of the SVC. The scheme finds multiple disjoint paths and a backup path for each destination. Paths are selected according to link achievable rate and video quality requirement. The resultant overlay topology shows certain level of tolerance to network dynamics, with computation overhead and network coding transmission overhead. As nearby links may interfere with each other, the work employs a clustering scheme that for each link e, all its nearby links are clustered together with it with a total cluster throughput restrained to be less or equal to that of e, as other links in the cluster can't be activated while e is busy. The resource allocation of the backup path i.e., the percentage of video data that can be routed through the path, is controlled to reflect the tradeoff between the performance and the robustness of the overlay. Neighborhood overhearing is not assumed, so the effectiveness of network coding is limited to combining data that shares a link, rather than benefiting multiple neighboring nodes. Another similar optimized flow selection algorithm is proposed in [2].

The partner set selection is crucial in video broadcasting. One of the key design consideration is to choose appropriate partners to ensure proper streaming rate, while keep potential interferences low. With one-hop broadcast enabled, nodes that are currently already serving the requested content to others should be preferred to be the supplier of a new node to avoid additional transmissions. Another issue is how to design a backup policy to maintain streaming quality in case of insufficient partners. Use of Multi-hop paths to nodes further away reduces the possibility of such cases, but is vulnerable to network dynamics, and may harm the network throughput due to per-hop interference. Pulling directly from AP is resilient to network dynamics, with a possible increase of streaming cost.

3 Structured overlay

In structured overlay, a broadcast spanning tree is continuously maintained so that the routes to all the clients via this tree are readily available for streaming. The major advantage of such proactive, tree-based overlay construction is its shorter routing delay and less redundant transmissions. However, a higher control overhead is normally required to maintain routes, because control information needs to be periodically exchanged and the overlay continuously updated due to network dynamics, even when there is no data. There are two major approaches of overlay construction in this category, namely, single-tree and multi-tree.

3.1 Single-tree Overlay

In single-tree overlay construction, mobile nodes form a broadcast tree spanning all the nodes as illustrated in Fig. 3. Video stream is delivered to each node by simply following the tree branches. The tree can be computed either centrally or in a distributed manner. Centralized algorithms often require a "leader node", usually being the tree root, to collect global topological information and to compute

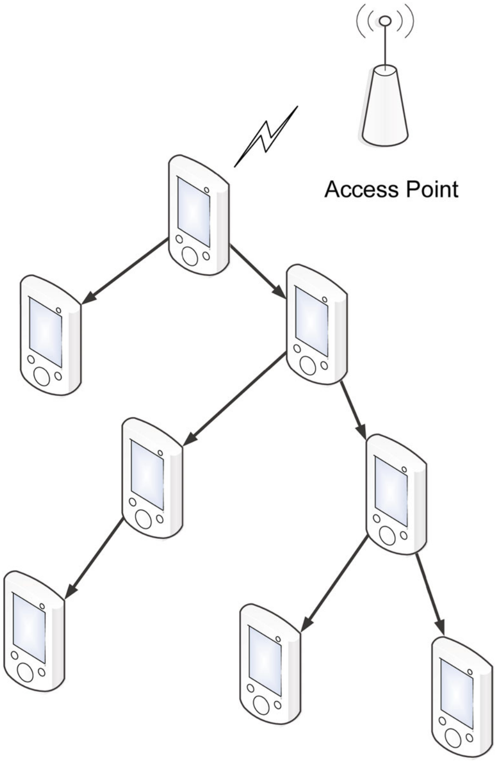

Fig. 3 A P2P multicast tree built among mobile peers

the optimal tree. The computed result is then distributed to the peers. This is in contrast to distributed algorithms, where each node chooses its parent independently in a distributed manner. In any case, the broadcast tree is often computed by taking advantage of wireless broadcasting. Usually the design objective is to solve the minimum transmission broadcast (MTB) problem, which often leads to the following properties:

- In reliable networks, each transmission is assumed to be always successful. Minimum transmissions then is equivalent to minimum number of relays, which effectively reduces the problem to a maximum leaf spanning tree (MLST) problem;
- In unreliable networks, losses are often recovered by per-link retransmission, therefore link conditions, e.g., ETX, need to be taken into consideration for transmission number minimization.
- The objective conserves network-wise energy, while individual clients, if near the top of the tree, may experience an unfair energy drain;
- Once the tree is established, routing becomes straightforward by simply pushing packets along the tree branches through broadcasting. Comparing to gossip-like routing algorithms, this efficiently reduces routing complexity and delay.
- The reduced number of relay nodes are often "sparsely" separated, reducing potential signal interferences and collisions.

Much research work on mobile P2P streaming are single-tree based. An example is **CLAPS** (Cross-Layer and P2P based Solution), which is based on **MOST** (Multicast Overlay Spanning Tree) [32]. MOST adapts and extends the standard wireless multi-hop routing protocol **OLSR** (Optimized Link State Routing Protocol) [9, 34]. Similar to other link-state routing protocols, OLSR exchanges link state and topology information by flooding the network using some "relays" called *Multi-Point Relay (MPR)*. This protocol is optimized for wireless environment in that it makes use of one-hop broadcasting and tries to reduce the number of MPRs. The set of MPRs of each node is selected by each node out of its direct neighbors. The principle of MPR selection is that data from a node, through its chosen MPR neighbors, can reach all its 2-hop neighbors. As a result, link-state information can be flooded throughout the network in a controlled manner by only using these MPRs as relays. In other word, the set of all MPRs *dominates*[4] the network. MOST computes an optimal overlay multicast tree over the set of all the MPRs. In order to achieve and maintain a unified view of the multicast group members across the group, node join message is periodically broadcasted throughout the network by the *MPR-flooding mechanism* introduced in OLSR. CLAPS uses the global tree built by MOST for routing table construction, message delivery and topology computation.

CLAPS takes advantages of one-hop broadcasting by making use of the dominating set concept. This design can effectively reduce the number of relays while maintaining a high probability that the streaming service reaches all users. To address relay selection as well as topology dynamics, CLAPS employs OLSR protocol, especially its efficient MPR selection algorithm and MPR-flooding mechanism. This overhead, although higher than that in mesh-based schemes, does not increase with the amount of data to be distributed as often exhibited in mesh-based schemes.

Chen et al in [7] employs a game-based distributed parent selection algorithm called **GB-BTC** for MTB tree construction. For a reliable network, the payoff of employing an intermediate node is uniformly shared by all of its children. Say a node i has c children, then each has a payoff of $-1/c$. In the process of maximizing individual payoffs, each node will prefer to select the neighbor node with maximum number of children as its parent. The process effectively reduces the opportunity that new intermediate node is introduced whenever possible. For an unreliable network, the payoff of a node considers the ETX of the link between the node and its chosen parent. More precisely, if node u selects node v as its parent, with the link delivery ratio p_{vu}, then the payoff of node u is $-(1/c + (1 - p_{vu})/p_{vu})$, given that node v already has $c - 1$ children. Readers are referred to [7] for the corresponding deduction. Obviously, a link with high delivery ratio from a neighbor already serving many children can effectively increase the payoff of a new child. The parent updating strategy at each nodes runs repeatedly until a Nash Equilibrium is arrived. Note that GB-BTC is not specifically for video broadcasting, but rather for building a general broadcasting tree. Extra constraints, such as link capacity, delay constraint etc., need to be considered for video distribution.

Game-theory based algorithms with their implementation simplicity and the ability of running distributedly, are suited for parent-child relationship establishment. However when applying game theory, several issues need to be addressed:

- *Proof of convergence:* Since each node repeatedly updates its own strategy in response to neighboring nodes' strategy change, it is necessary to show that the game terminates in a finite number steps. The game played in GB-BTC is shown to be an *exact potential game*, which guarantees the convergence.
- *Performance:* When the algorithm converges, although each node individually have reached a local optimal, the performance of the network as a whole is unknown. In

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[4] A subset of nodes *dominates* the network if each node in the network is either in this set or has at least one direct neighbor in this set.

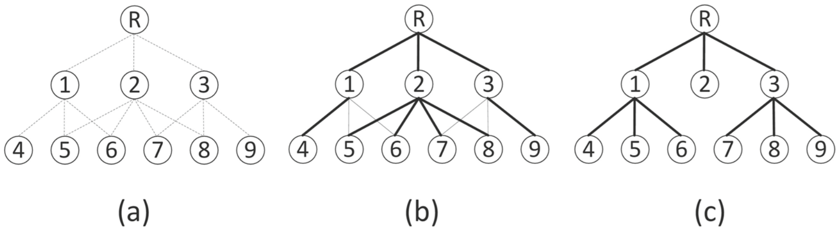

Fig. 4 An example showing a suboptimal Nash Equilibrium. Given the connectivity graph in (a), (b) and (c) are two possible Nash Equilibriums, while (c) outperforms (b) in terms of total number of transmissions

game theory, several concepts are developed to quantify the performance of an Nash equilibrium such as *Price of Anarchy (PoA)* and *social optimum*.[5] Figure 4 shows a simple example in which GB-BTC may terminate at one of two possible Nash equilibriums with different performances. Given the connectivity graph in (a) with reliable links, nodes 5,6,7,8 can choose node 2 to be their parents each with the highest payoff of $-1/4$; however node 4 and 9 have to choose node 1 and 3 as their corresponding parents. The resultant overlay is shown in (b), in which nodes 1,2,3 are all relay nodes, with total number of transmissions to be four, and no single node can improve itself; in (c), nodes 5, 6 are children of node 1 with a lower payoff of $-1/3$, same with nodes 7,8. The total number of transmission is three as of now node 2 is a leaf node.

- *Connectivity assurance and cycle avoidance:* Since each node is allowed to choose its own streaming parent, there is in general no guarantee that the resultant overlay is a connected tree without cycles. In short, the situation in which a node chooses its descendant as relay parent should be avoided. An example of a partitioned outcome is given in [7]. One possible solution as used in their work is to assign a rank to each node with its shortest hop distance to source node, and force the rank be strictly non-decreasing along any path and to increase within 2 hops to eliminate the minimal possible cycle between two nodes. Note that constraints like this may further downgrade the overlay performance as certain overlay topologies are prohibited.

In a more recent work, Chang et al in [6] proposed **PNCB** to build a broadcast tree for each video broadcasting source, assuming multiple sources each broadcasting a different video stream. **PNCB** tries to minimize the total number of transmissions with link sharing and network coding. With the insight that the minimum number of transmissions required at any node is lower bounded by the maximum number of trees that select a common outgoing link from this node, denoted as the node's max out-degree. Consequently, a neighboring node is preferred to be the parent if doing so does not increase the neighbor's max out-degree. In other word, if link (i, j) is already a branch in many broadcast trees, then node j should avoid choosing i as the parent of future broadcast trees. With the use of network coding, it is possible to achieve the lower bound by combining packets of different trees before transmit. An example is shown in Fig. 5. Node B and C each chooses node A as parent of one of the two broadcast trees (denoted by the solid link and dotted link). As each link is only involved in a single tree, the max out-degree for node A is 1. And indeed node A only need to transmit the NC combined packet once to fulfill both B and C. Note that in the assumed multi-source broadcast scenario, both B and C should be able to get the other packet from a different parent, thus allowing them to perform NC decoding of the packet sent by A successfully.

As seen from above, building and maintaining a global tree is not trivial. One major issue of a global tree is to achieve an extended lifetime for the constructed tree, and hence to maintain network connectivity in the presence of peer churn/mobility. Some of the research topics in this regard are:

- *Relay selection:* The interior nodes or relays need to be appropriately selected. On one hand, they should not be chosen too close with each other, causing unnecessary interference and transmission collision. On the other hand, they cannot be too sparse to cause network disconnection.

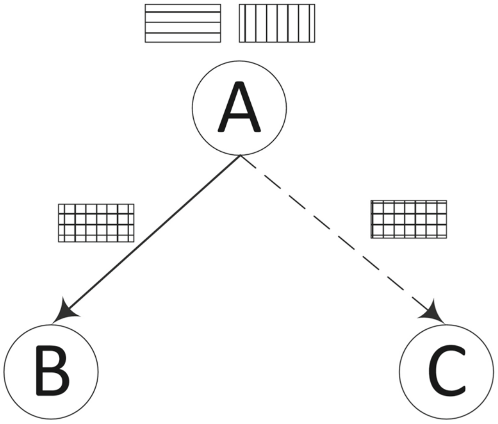

Fig. 5 In this example, with network coding, PNCB is able to transmit once to deliver data to its children in different broadcast trees

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[5] Audiences are referred to game theory materials for detailed information.

- *Global tree convergence time:* For centralized tree construction, this convergence time is contributed by information aggregation, central computation and result distribution. Distributed tree construction algorithms often construct trees iteratively through interactions among nodes. This often takes time for all participants to come to an agreed overlay.
- *Mobility issues:* If the network topology changes faster than tree convergence time, the tree may not be able to converge to the steady state. Therefore, schemes must be devised to address different level of user mobility. Furthermore, mobility may affect network conditions and how to deal with transmission errors becomes important.

3.2 Multi-tree Overlay

In single-tree approach, leaf nodes often suffer from high loss due to error propagation and the delay between unexpected disconnections and subsequent parent negotiations. Multi-tree approach tries to address this by constructing multiple trees for concurrent use. It usually makes use of substream video coding schemes such as multiple description coding (MDC) and scalable video coding (SVC), and constructs multiple trees each for a description/layer of the video.

Osamah et al. propose a mobile P2P streaming algorithm with multiple trees in [4]. To address the heterogeneity of node capacities and to utilize links with low throughput, a multi-tree overlay structure is used. Video is encoded using SVC, and each tree transmits one layer. All nodes have to first join the base-layer spanning tree in order to receive the base layer. Depending on the residual capabilities of each node, they may incrementally join trees of higher enhancement layers to receive the corresponding layer and improve their video quality. In the example shown in Fig. 6, solid lines form a spanning tree to transmit the base layer, while dotted lines form a tree to transmit an enhancement layer. Nodes and edges with higher capacities appear in more trees and receive more layers. The system utilizes low capacity links and delivers video streams of different aggregated qualities to nodes with corresponding capacities.

Both the multi-tree topology (given by tree-based overlay construction) and the *mesh* topology (given by mesh-based overlay construction) allow a node to receive data from multiple suppliers. However, in multi-tree approach, each piece of data traveling through the network strictly follows its designated tree branches using push operation, while in mesh each piece of data goes through an individually formed path that may be changed at any time in an ad-hoc manner. As a result, while a mesh is simpler to implement, multi-tree approach has more room for performance optimization and often achieves lower delay.

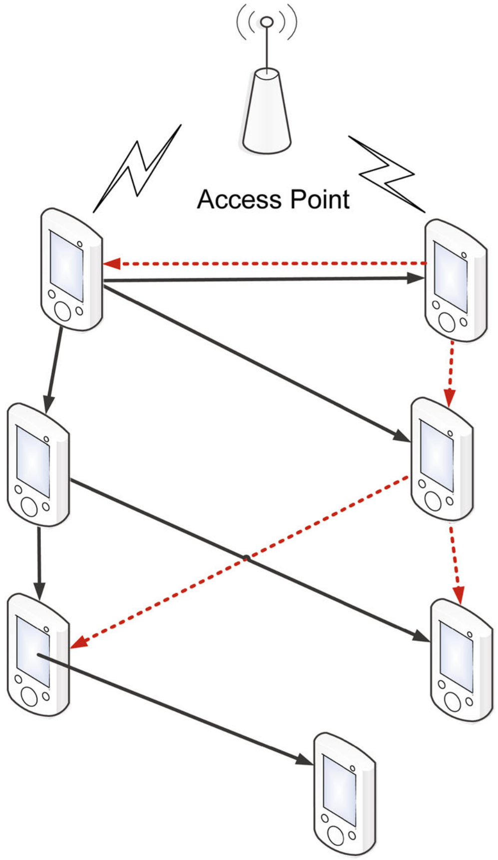


Fig. 6 Two trees built among peers using SVC streams

4 Hybrid overlay

Hybrid overlay topology, often referred to as structured mesh, is to combine the strengths of both unstructured mesh approach and tree approach. When designing a hybrid overlay structure, one needs to consider the following:

- *Overlay structure:* Combining and utilizing the strengths of both types of topologies is the major motivation of hybrid topologies. In order to achieve that, hybrid overlays are often constructed either by extending tree structure with redundant mesh connections, or by optimizing the existing mesh overlay with tree-like connectivity.
- *Measurement of node goodness:* Different nodes may play different roles in a hybrid overlay topology. The roles may be due to parameters such as their stability, available energy, mobility, etc. The performance of a hybrid scheme is affected by the timeliness and accuracy in measuring these parameters. Previously proposed measurement schemes range from as simple as age-based approach (i.e., based on how long a node has stayed in the network) to as complex as the weighted aggregation of multiple network parameters.

- *Control overhead:* In constructing a hybrid overlay, there may be different control messages needed to achieve different objectives (search, connections, data exchange, etc.). Proper management of control messaging by combining and simplifying those messages leads to bandwidth efficiency. A hybrid overlay protocol should be light-weight with low control overhead.

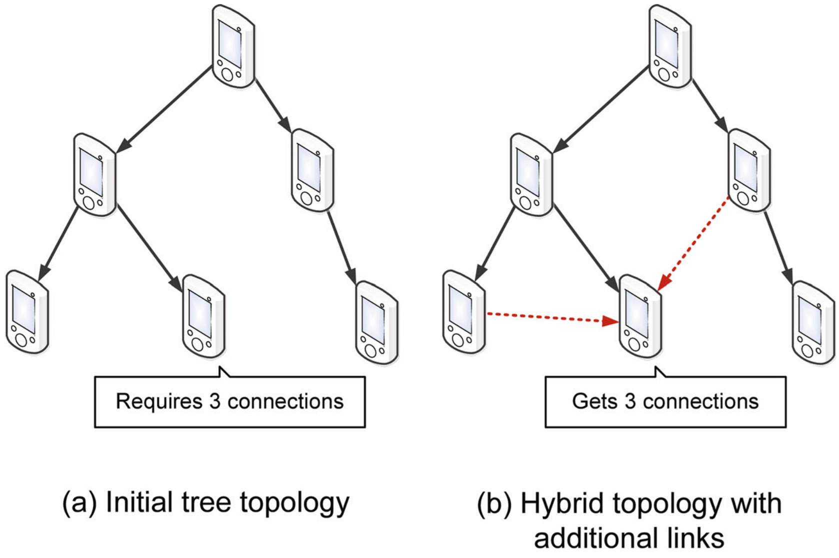
The early work **mTreebone** proposes to combine the advantages of both tree and mesh [38]. Although this work is for the Internet, it emphasizes the importance of selecting "stable nodes". In mTreebone, stable nodes are identified to build a backbone tree. All the nodes, both stable and unstable, also form a *pull*-based mesh overlay. Stable nodes are identified according to their ages, based on an earlier work stating that for large scale interesting broadcasts, nodes have stayed in the network for a long time tends to stay longer [5]. One of the key issues in most structured overlay establishment algorithms is how to correctly and timely identify node stability. Aforementioned age-based prediction is one of the widely used schemes. Since mTreebone focuses on wired network, most nodes are assumed stable in order to avoid the entire network falling back to the unstructured mesh overlay. In more common mobile network scenarios where most nodes are mobile, it is difficult to apply mTreebone with a noticably improved performance.

Targeting at wireless network, two types of hybrid architectures are introduced, namely interleaved hybrid and tiered hybrid [19, 21]. Interleaved hybrid topology tries to make good use of link residual bandwidth in tree structure [19]. As shown in Fig. 7, if a node gets insufficient streaming rate from the tree topology and requires two more connections, additional links may be inserted to existing tree structure to fulfill this node. To achieve overall good streaming performance, nodes with higher *communication quality* (i.e., high bandwidth and low loss rate) are put nearer to source node. With additional links, a desired degree of connectivity can be achieved. Furthermore, differentiated service is enabled to serve nodes with heterogeneous capacities. Using this scheme, links with low bandwidth can be more efficiently utilized. As this topology can be formed by simple extension of existing tree topologies, the control overhead is comparable with the corresponding tree construction algorithm.

Instead of targeting at connectivity as in interleaved hybrid schemes, tiered hybrid topology focuses on utilizing nodes with high capabilities. Works in [21] propose to classify nodes with *relay ability*. Node relay ability is a function of multiple variables, such as available bandwidth, user preference, battery power, etc. As shown in Fig. 8, nodes with relay abilities higher than a threshold form a tree. The rest of the nodes, while supported by the tree, form a mesh network for better sharing. On one hand, this tiered hybrid topology utilizes nodes with high relay abilities in tree construction, resulting in an increased tree throughput and an extended tree lifetime. On the other hand, unstructured mesh topology formed among the rest of the nodes is resilient to network dynamics.

Both interleaved hybrid topology and tiered hybrid topology are based on the extension and modification from an existing global *tree* structure. This is in contrast to another work called **LocalTree** [42], which aims at optimizing an unstructured *mesh* with tree structures. In LocalTree, new joiners initially run gossip-based partner selection algorithm and form an unstructured mesh. Relatively stable node groups (based on link transmission success rate and node relay probability) are then identified in a distributive manner. Link transmission success rate is defined as the ratio between number of received packets and the number of sent packets. Node relay probability is defined as the probability that a node will relay its received packets. Node relay

Fig. 7 An interleaved hybrid architecture formed among peers



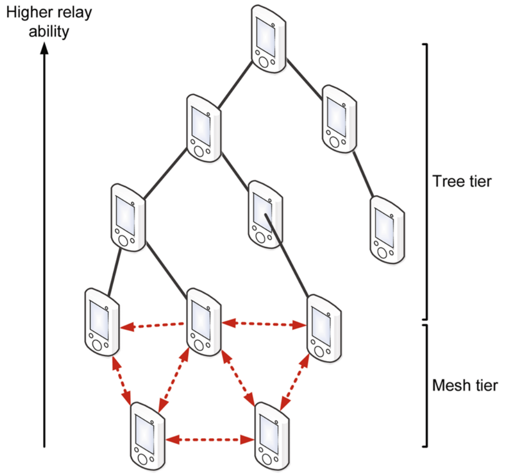


Fig. 8 A tiered hybrid architecture formed among peers

probability may be affected by parameters such as node's residual battery power. Within each node group, a locally optimized broadcast tree is computed, leading to more efficient intra-group streaming. The resulting overlay structure is a hybrid structure, with unstructured mesh formed as a whole, and small locally optimized broadcast trees in certain stable areas. Figure 9 shows an example topology resulted from using LocalTree. Node 1 pulls the stream from the base station. The connections in the unstructured mesh are indicated by the dotted lines. Nodes 2 and 3 are the roots of the two disjoint local trees $C1$ and $C2$, as indicated by solid lines at the tree tier. Note that the tree computation algorithm is modified to allow multiple parents, in order to achieve appropriate transmission rate and certain degree of robustness. So the resulting structure in each local group may be a directed acyclic graph (DAG) instead.

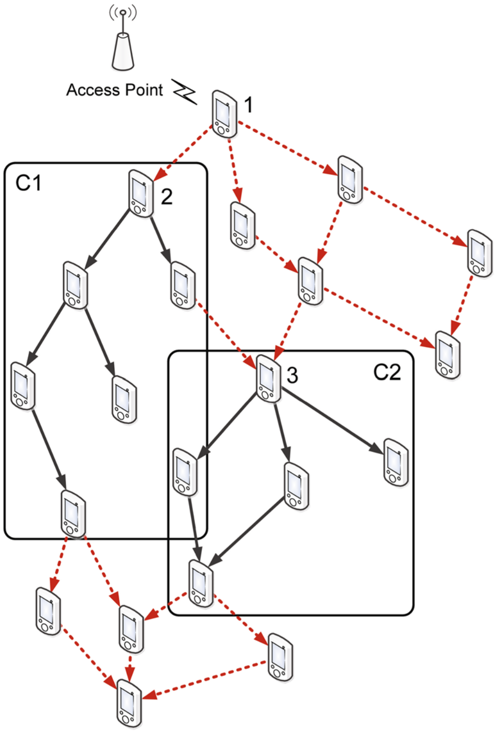


Fig. 9 Illustration of two *localtrees* formed in a mobile network

5 Comparison

We compare the performance of mesh, tree and hybrid approaches in this section. We choose push-based unstructured mesh, global tree and LocalTree as the representative schemes of these approaches.

In our simulation, a number of nodes are randomly placed in a square area of size 200x200 units, each with the transmission range of 50 units. For a particular sender-receiver pair in LocalTree, the *transmission reliability* is defined as the product of link transmission success rate and sender's relay probability. Clearly, a high transmission reliability suggests that the channel has high success rate and nodes are more willing to relay. Note that a chosen relay in any algorithm may or may not actually perform the relay either intentionally or due to node failure. Transmission reliability doesn't reflect the effect of interference. Multiple concurrent transmissions, each with high transmission reliability, may all fail to deliver if they interfere with each other. Transmission reliability increases due to either the increase of link delivery ratio or client relay probability.

Figure 10 illustrates packet loss rates, i.e., the percentage of packets failed to reach receivers, versus transmission reliability. As the network becomes more reliable, the loss rate of all three algorithms decreases. In the most unreliable network, global tree suffers from constant overlay reconstruction, hence experiences very high loss rate. Unstructured mesh with independent relays, maintains a relatively

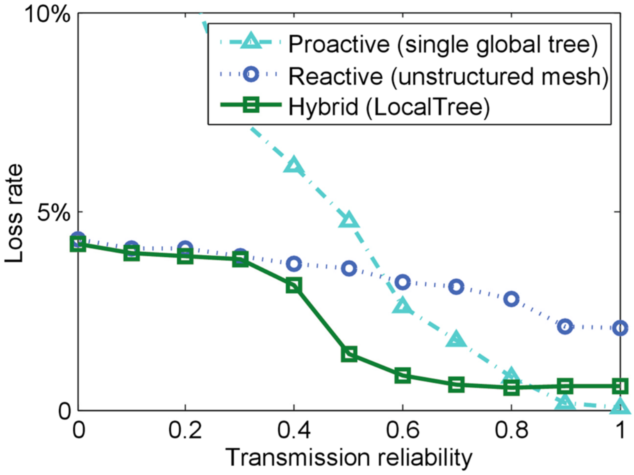


Fig. 10 Loss rate versus transmission reliability

low loss rate. With the increase of transmission reliability, the success rate of relays in unstructured mesh becomes higher, resulting a reduced loss. Global tree algorithm with optimized overlay, benefit from high transmission reliability, shows a rapid decrease of loss rate. LocalTree scheme performs similarly to unstructured mesh when transmissions are unreliable, and quickly converges to global tree scheme in reliable network. This is due to the effective combination of unstructured overlay and opportunistic local optimized tree construction in LocalTree. When the network is stable, many small trees can be built locally in different areas of the network. These trees are connected to form an efficient global overlay structure optimized to the degree similar to global tree. In unreliable networks, LocalTree falls back to unstructured overlay to avoid transmission interruption and frequent overlay reconstruction as in global tree approach.

Figure 11 shows the number of relays selected versus network reliability. The global tree algorithm shows a drastic drop of the number of relays as the tree can be built easier with less interruption. The overhead of unstructured mesh stays roughly unchanged as the amount of the control message is insensitive to network conditions. LocalTree performs as the unstructured algorithm when the network is unreliable, and gradually start to try to build small trees. At first most of the trees are failed to build, resulting an increased overhead. As the network becomes more reliable, local trees can be successfully built. LocalTree finally converges to the global tree algorithm in terms of selecting optimal relays.

Average end-to-end streaming delay in terms of hop count is shown in Fig. 12. When transmissions are not reliable, a global tree can hardly be built, leading to high average delay. It is however able to achieve the lowest delay when transmissions are reliable. Average delay for unstructured mesh only marginally drops as transmissions become more reliable. LocalTree again is shown effectively combining the strength of both tree-based and mesh-based schemes.

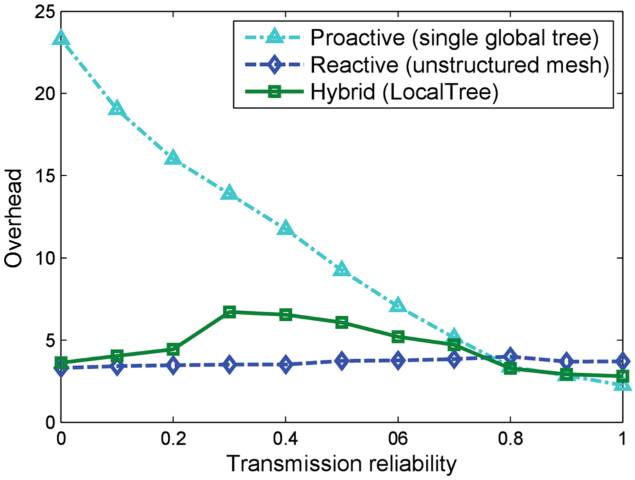


Fig. 11 Overhead versus transmission reliability

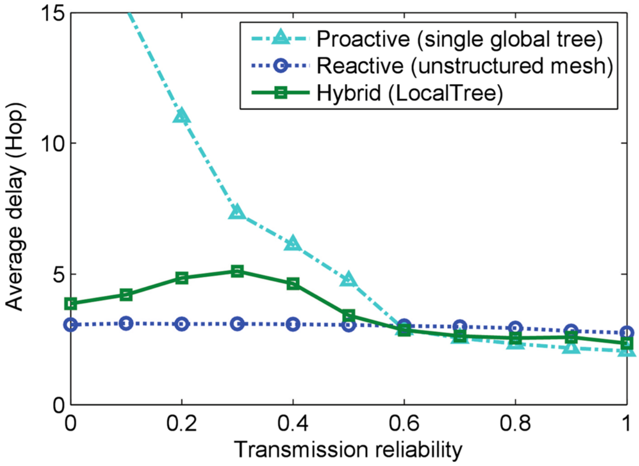


Fig. 12 Average delay versus transmission reliability

Figure 13 shows the energy cost for different network size in static network. For unstructured algorithm and global tree algorithm, energy cost is defined equal to the number of relays chosen by the algorithm. For LocalTree, since a chosen relay may not always relay its stream, as indicated by node relay probability, the energy cost is defined as the sum of the relay probability over all chosen relays. In other words, it represents the actual number of relays used. Although higher than the global tree algorithm, the energy cost of LocalTree is much lower than the unstructured algorithm.

Besides quantitative comparison, we show in Table 1 qualitative comparisons on the strengths and weaknesses of different overlay structures. Conventional client-server architecture performs well in terms of delay, fairness and maintenance complexity, given that the number of clients is small, but without the ability to extend the service beyond AP coverage. Its performance also drops sharply as the

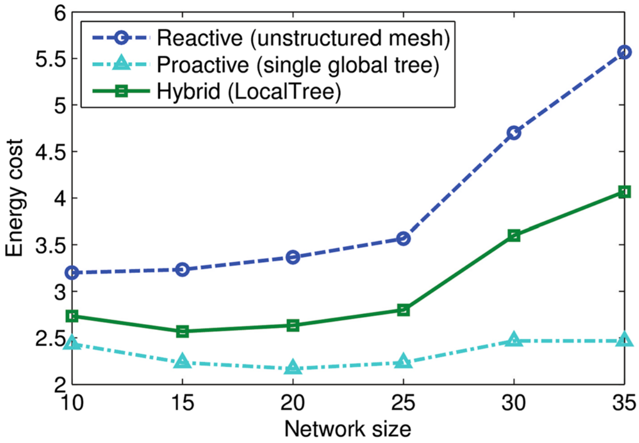


Fig. 13 Energy cost versus network size

Table 1 The comparison of different system architectures

	Single hop (client-server)	Multi-hop (wireless P2P)			
Overlay architecture	Star	Tree	Multi-tree	Unstructured	Hybrid
Service allocation	Request to AP	Parent		neighbors	neighbors
AP workload	Support all nodes	Support tree(s) root(s)		Support puller(s)	Support pullers
Data delivery direction	Pull	Push		Pull/Push	Pull/Push
Overlay routing	1-hop	Follow tree(s) branches		1-hop broadcast with gossip-like relay	Design specific
Service coverage (connected)	Nodes near AP	Nodes on/near any tree		All nodes	All nodes
End-to-end delay	Short	Short (depends on tree depth)		Indefinite	Indefinite (optimizable)
Overlay maintenance complexity	N/A	High	Highest	Low	Median to high
Robustness to network dynamics	Good	Requires fast converge	Good until all trees break	Good	Good
P2P link utilization	N/A	Good	Better	Good	Good
High density effect	Negative	Positive		Positive	Design specific
Fairness	Perfect	Unfair to non-leaf nodes		Good	Design specific
Potential weaknesses	AP bottleneck Service coverage	Overlay maintenance Convergence duration		Flooding control No delivery guarantee	Overlay maintenance
Examples	Most current commercial systems	CLAPS [32], PNCB [6]	MSMT [4], GB-BTC [7]	COSMOS [22], Li et al. [23]	Interleave [19], Tiered [21], LocalTree [42]

client density increases, as AP quickly becomes the bottleneck and is overwhelmed by requests. The major advantages of multihop overlay structure, by utilizing secondary network, are reduced server/AP load and extended service coverage. Unstructured overlay with almost no explicit overlay maintenance, is proposed to mainly cope with network dynamics, but may experience excessive transmission redundancy and unpredictable delay. Broadcast tree based overlay is able to minimize either delay or network traffic, but at the cost of convergence delay, and high overlay maintenance complexity. Furthermore, relay fairness needs to be considered in tree construction, to make sure data relay task is not limited to a small group of clients. Different types of hybrid overlays are proposed, trying to utilize the strength of unstructured overlay and tree overlay. Appropriate hybrid overlay design can effectively overcome above shortcomings. For hybrid designs however, computational complexity and control overhead need to be carefully considered.

6 Open research directions

With the development of wireless networks and devices, and the fact that infrastructure wireless networks are yet to meet the stringent requirements in wireless video broadcasting, P2P schemes with client cooperation is becoming, and will undoubtedly be the dominating approaches in such services. As it becomes more and more important, several fundamental challenges in building the overlay for such service are yet to be solved to a satisfactory, as we have discussed and listed in previous sections.

We envision future overlay designs for cooperative wireless live video streaming may become more application-oriented. In particular, the following aspects are likely some of the areas of focus:

- *QoS-awareness:* The overlay may be adaptive to different quality requirements. For interactive applications such as video conferencing, delay is crucial, while moderate loss rate is only secondary. A related topic is heterogeneous quality requirements, in which different clients have different quality preference (delay, quality, etc.) for the same video distribution session, leading to different overlay construction principles for different clients.
- *Video format-awareness:* Although some work has proposed overlays for video coding structures such as MDC, SVC, the full utilization of different coding structures and the comprehensive performance study are still immature. Furthermore, few have considered building an overlay for heterogeneous coding structures. Another topic related to video coding is to support 3D video, which is getting more and more popular.

- *Utilization of multiple channels/interfaces:* In near future mobile devices may carry multiple interfaces, allowing them to communicate with multiple neighbors with different messages simultaneously using different channels.

7 Conclusion

The broadcast nature of wireless transmissions and topology dynamics of wireless P2P networks bring challenges to the overlay design of a P2P streaming system over such a network. They lead to many crucial design considerations discussed in this survey. We have reviewed some of the recent designs divided into three categories: unstructured, structured, and hybrid approach. Mesh based approaches often lead to unstructured mesh overlays. Robustness to network dynamics and maintenance simplicity are its major advantages. However unpredictable streaming delay and high traffic redundancy are its main shortcoming. Advantages of tree based schemes include bandwidth utilization and low routing delay. However, taking mobility into account, tree construction, maintenance and recover may greatly increase algorithm complexity.

We have discussed in detail the design issues and challenges in each category as well as each approach. We present qualitative comparisons of each category, as well as quantitative comparisons of example schemes from each category. With research bodies continue to improve current approaches, future proposals may become more and more application-oriented, and are highly optimized for a narrower set of applications, rather than a one-for-all general framework.

Acknowledgments This work was supported, in part, by Hong Kong Research Grant Council (RGC) General Research Fund (610713).

References

1. Ken Yiu W-P, Jin X, Gary Chan S-H (2007) Challenges and Approaches in Large-Scale Peer-to-Peer Media Streaming. IEEE Multimedia Magazine 14(2):50–59
2. Abdel Khalek A, Dawy Z (2011) Energy-efficient cooperative video distribution with statistical QoS provisions over wireless networks. IEEE Trans Mob Comput PP(99):1
3. Alnuweiri H, Rebai M, Beraldi R (2012) Network-coding based event diffusion for wireless networks using semi-broadcasting. Ad Hoc Netw 10(6):871–885
4. Badarneh O, Kadoch M, ElHakeen A. (2008) Multilayered video multiple trees multicast algorithms for heterogeneous wireless ad hoc networks. In: Network Computing and Applications, pp 220–223
5. Bishop M, Rao S, Sripanidkulchai K (2006) Considering priority in overlay multicast protocols under heterogeneous environments. In: Proceedings of 25th IEEE International Conference on Computer Communications, pp 1–13
6. Chang CH, Kao JC, Chen FW, Cheng SH (2014) Many-to-all priority-based network-coding broadcast in wireless multihop networks. In: Wireless Telecommunications Symposium (WTS), pp 1–6
7. Chen FW, Kao JC (2013) Game-based broadcast over reliable and unreliable wireless links in wireless multihop networks. IEEE Trans Mob Comput 12(8):1613–1624
8. Chen T, Zhong S (2014) An enforceable scheme for packet forwarding cooperation in network-coding wireless networks with opportunistic routing. IEEE Trans Veh Technol 63(9):4476–4491. doi:10.1109/TVT.2014.2312171
9. Clausen T, Jacquet P (2003) Optimized link state routing protocol. RFC3626
10. Fan Y, Jiang Y, Zhu H, Shen X (2010) PIE: cooperative peer-to-peer information exchange in network coding enabled wireless networks. IEEE Trans Wirel Commun 9(3):945–950. doi:10.1109/TWC.2010.03.090675
11. Frias VC, Delgado GD, Igartua MA, Delgado JA, Diaz JM (2005) QoS provision for video-streaming applications over ad hoc networks. In: EUROCON, vol 12, pp 640–643
12. Gharavi H, Ban K (2003) Cross-layer feedback control for video communications via mobile ad-hoc networks. In: Vehicular Technology Conference, vol 5, pp 2941–2945
13. Hao Y, Tang J, Cheng Y (2013) Secure cooperative data downloading in vehicular ad hoc networks. IEEE Journal on Selected Areas in Communications 31(9):523–537. doi:10.1109/JSAC.2013.SUP.0513047
14. He S, Chan SHG, Yu L, Liu N (2015) Fusing noisy fingerprints with distance bounds for indoor localization. In: Proceedings of The 34th Annual IEEE International Conference on Computer Communications (INFOCOM 2015), pp 2506–2514. Hong Kong
15. He S, Li X, Chen J, Cheng P, Sun Y, Simplot-Ryl D (2013) EMD: Energy-efficient p2p message dissemination in delay-tolerant wireless sensor and actor networks. IEEE Journal on Selected Areas in Communications 31(9):75–84. doi:10.1109/JSAC.2013.SUP.0513007
16. Jinfeng Z, Jianwei N, Rui H, Jianping H, Limin S (2007) P2P-leveraged mobile live streaming. In: 21st International Conference on Advanced Information Networking and Applications Workshops (AINAW'07), vol 2, pp 195–200
17. Kang X, Wu Y (2014) Incentive mechanism design for heterogenous peer-to-peer networks: A stackelberg game approach. IEEE Trans Mob Comput PP(99):1. doi:10.1109/TMC.2014.2343628
18. Koutsonikolas D, Hu Y, Wang CC (2012) Pacifier: High-throughput, reliable multicast without "crying babies" in wireless mesh networks. IEEE/ACM Trans Networking 20(5):1375–1388. doi:10.1109/TNET.2011.2177274
19. Kubo H, Shinkuma R, Takahashi T (2009) Mobile overlay multicast using information on physical stability for robust video streaming. In: IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications, pp 2960–2964
20. Kubo H, Shinkuma R, Takahashi T (2010) Mobile P2P multicast based on social network reducing psychological forwarding cost. In: IEEE Global Telecommunications Conference (GLOBECOM'10), pp 1–5
21. Kubo H, Shinkuma R, Takahashi T (2010) Topology control using multi-dimensional context parameters for mobile P2P networks. In: IEEE 71st Vehicular Technology Conference (VTC 2010-Spring), pp 1–5
22. Leung MF, Chan SHG (2007) Broadcast-based peer-to-peer collaborative video streaming among mobiles. IEEE Transactions on Broadcasting Special Issue on Mobile Multimedia Broadcasting 53(1):350–361

23. Li C, Xiong H, Zou J, Chen CW (2012) Distributed robust optimization for scalable video multirate multicast over wireless networks. IEEE Transactions on Circuits and Systems for Video Technology 22(6):943–957
24. Li Y, Zhang Z, Wang C, Zhao W, Chen HH (2013) Blind cooperative communications for multihop ad hoc wireless networks. IEEE Trans Veh Technol 62(7):3110–3122. doi:10.1109/TVT.2013.2256475
25. Liu X, Cheung G, Chuah CN (2009) Structured network coding and cooperative wireless ad-hoc peer-to-peer repair for WWAN video broadcast. IEEE Trans Multimed 11(4):730–741
26. Liu Z, Cheung G, Chakareski J, Ji Y (2015) Multiple description coding and recovery of free viewpoint video for wireless multi-path streaming. IEEE Journal of Selected Topics in Signal Processing 9(1):151–164. doi:10.1109/JSTSP.2014.2330332
27. Liu Z, Feng J, Ji Y, Zhang Y (2014) Adaptive energy-aware free viewpoint video transmission over wireless networks. In: International Conference on Computing, Networking and Communications (ICNC), pp 157–162. doi:10.1109/ICCNC.2014.6785323
28. Liu Z, Feng J, Ji Y, Zhang Y (2014) EAF: Energy-aware adaptive free viewpoint video wireless transmission. J Netw Comput Appl 46:384–394. doi:10.1016/j.jnca.2014.07.010
29. Mejia M, Pena N, Munoz JL, Esparza O, Alzate MA (2011) A game theoretic trust model for on-line distributed evolution of cooperation inmanets. J Netw Comput Appl 34(1):39–51. http://www.sciencedirect.com/science/article/pii/S1084804510001694
30. Moleme N, Odhiambo M, Kurien A (2009) Enhancing video streaming in 802.11 wireless mesh networks using two-layer mechanism solution. In: AFRICON 2009, pp 1–6
31. Nguyen D, Nguyen T, Yang X (2007) Multimedia wireless transmission with network coding. In: IEEE 16th International Packet Video Workshop, pp 326–335. Lausanne, Switzerland
32. Niraula NB, Kanchanasut K, Laouiti A (2009) Peer-to-peer live video streaming over mobile ad hoc network. In: International Conference on Wireless Communications and Mobile Computing, pp 1045–1050
33. Park JS, Gerla M, Lun DS, Yi Y, Medard M (2006) Codecast: a network-coding-based ad hoc multicast protocol. In: IEEE Wireless Communications, vol 13, pp 76–81
34. Rodolakis G, Naimi AM, Laouiti A (2007) Multicast overlay spanning tree protocol for ad hoc networks. Wired/Wireless Internet Communications 4517:290–301
35. Seferoglu H, Markopoulou A (2007) Opportunistic network coding for video streaming over wireless. In: Packet Video, pp 191–200
36. Setton E, Yoo T, Zhu X, Goldsmith A, Girod B (2005) Cross-layer design of ad hoc networks for real-time video streaming. In: IEEE Wireless Communications, vol 12, pp 59–65
37. Sinkar K, Jagirdar A, Korakis T, Liu H, Mathur S, Panwar S (2008) Cooperative recovery in heterogeneous mobile networks. In: 5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON'08), pp 395–403
38. Wang F, Xiong Y, Liu J (2010) mTreebone: A collaborative tree-mesh overlay network for multicast video streaming. IEEE Transactions on Parallel and Distributed Systems 21(3):379–392
39. Wu J, Cheng B, Yuen C, Shang Y, Chen J (2015) Distortion-aware concurrent multipath transfer for mobile video streaming in heterogeneous wireless networks. IEEE Trans Mob Comput 14(4):688–701. doi:10.1109/TMC.2014.2334592
40. Wu S, He C (2011) QoS-aware dynamic adaptation for cooperative media streaming in mobile environments. IEEE Transactions on Parallel and Distributed Systems 22:439–450
41. Zhang B, Chan SHG, Cheung G (2014) Peer-to-peer error recovery for wireless video broadcasting. Springer Peer-to-Peer Networking and Applications:1–13. http://dx.doi.org/10.1007/s12083-014-0297-8
42. Zhang B, Chan SHG, Cheung G, Chang E (2011) LocalTree: An efficient algorithm for mobile peer-to-peer live streaming. In: Proceedings of IEEE International Conference on Communications (ICC)

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