Mediating Multimedia Traffic With Strict Delivery Constraints

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***Abstract*—Internet multimedia traffic currently occupies more than half of the total Internet traffic and it continues to expand tremendously. Targeting to meet strict constraints imposed by the requirements of real-time multimedia applications appropriate error correction techniques should be implemented within the data dissemination network. We propose to introduce multi-purpose relay nodes called Mediators into several positions within the tree networks typical for multicasting and broadcasting scenarios. By utilizing the error-correction domain separation paradigm in combination with selective insertion of the supplementary data from parallel networks, when the corresponding content is available, the proposed mechanism reduces the total network load and improves scalability of multicast/broadcast transmission. We share our view on how the existing application frameworks could benefit from the incremental deployment of the proposed mechanism. Experimental results confirm suitability and applicability of our assumptions.**

Keywords: Networking and QoS, DTV and broadband multimedia systems, IPTV & Internet TV

I. Introduction

Currently, the Internet faces the shift from pure text-based transmissions to high data rate transfers carrying high quality audio-visual content. Forecasts confirm that video will be predominant in the Future Internet: Even in 2012 Internet video transmissions will occupy more than 50% of the global consumer Internet traffic [1]. Today's approaches to cope with this development are manifold. IP-Multicast [24] was invented to ease the efficient one-to-many distribution of content but it is mainly used in managed company networks rather than in the open Internet. The failure of multicast [25] to achieve the wide spread adoption can be explained by several technical and economic factors, including complexity of the multicast network management and uncertainty in how to appropriately charge for the service in the case when sources and receivers belong to different domains. P2P networking also turns out to be a good distribution approach for content valuable for a wide audience. Due to the agnostic overlay construction process, triggered by the users themselves, the ISP lose control of the network transmissions and suffer from loss of revenue. Other shortcomings are the highly heterogeneous consumer access bandwidth and high churn rates. Newly P4P networks try to overcome some of these drawbacks by introducing interaction between P2P networks and the network topologies [7] but they also suffer from the aforementioned basic P2P challenges. Another suitable approach to handle the increasing amount of data volumes are content delivery networks (CDNs). Hereby, a cluster of surrogate servers, which are distributed across the network, is used to store copies of the origin content in order to increase content delivery quality, speed and reliability [14]. CDN challenges are synchronization and updating the cached content within the delivery network. An approach which basically tries to combine broadband IP communication and broadcasting is Dynamic Broadcast. Thereby, broadcasters can offer additional services over broadband connections to satisfy the consumer's needs. As a consequence, it will be possible to shift more content to the broadband which helps to save costs especially if the audience is fairly small [5]. This approach is currently influencing the Hybrid Broadcast Broadband TV standardization process [3]. Furthermore, in [6] the authors focus on broadcasting augmentation data for GPS, especially on the distribution of such data via IP datacasting.

Targeting real-time multimedia applications with specific constraints unveils the condition of taking care of timely delivery and meet residual loss requirements. Thus, this traffic type must be handled differently than data traffic in general. Furthermore, actual network topologies contain multiple different type of physical transmission channels like Ethernet, WLAN or 4G links. Error-correction mechanism must be adjusted individually to the different parts of the network in order to reduce the amount of redundantly sent data and provide a satisfying experience at the receiver at the same time.

This work proposes an evolutionary networking approach that has the potential to lower the required resources for multimedia applications. We are targeting the broadcasting and multicasting real-time transmission scenarios. Additionally we also consider such a new application scenarios as stereoscopic streams where the basic stream can be extended by a secondary one to allow a subset of device displaying the content. The rest of the devices are still receiving legacy streams.

The proposed solution is based on two ideas. First, we propose to reduce network load by tailoring error-correction schemes to both their application scope and underlying network topology. Furthermore, we introduce the concept of exploiting parallel networks insert data into the network where the supplementary data is available and is really needed. It leads to a relief of traffic in parts of the network. Eventually, the amount of saved load can then be spent to other services or to a larger number of receivers by using the actual network topology and devices.

To take care of timely delivery and an upper limit for residual errors at the receivers, both approaches make use of an error-correction domain separation [26]. We propose to implement these functions as operating modes of the multi-purpose nodes, which we call *Mediators* following their operating principle of mediating traffic between multiple network segments. Thereby, Mediator nodes introduced into the network where it is appropriate, divide subsequent links into several segments. This way non error-prone link are released from carrying redundant data required by error-prone links as it happens in traditional end-to-end environments.

The reminder of this paper is structured as follows. In Section II we identify the problem area. Section III defines the Mediators and their characteristics in different operation modes. Section IV explains the principles of location assignment for Mediator nodes. In Section V we review several applications for Mediator nodes, which demonstrate the benefits of the proposed approach. An experimental example is presented in Section VI and Section VII concludes the paper.

II. Problem Statement

The problem area considered in this work is identified as follows. We assume the data distribution structure is established in form of a tree $T = (V, E)$ of the size $|V| = N$. We consider multicasting and broadcasting transmission scenarios for real-time multimedia applications. The real-time traffic imposes a tight upper limit for its delivery time Δ and the residual error loss rate P_{target} at the receiver. To achieve the desired *quality of experience (QoE)* [22] both constraints must be completely satisfied. One of the following error correction schemes *forward error correction (FEC)*, *automatic repeat request (ARQ)* or *hybrid error-correction (HEC)* is applied for data protection.

The targeted applications are replenished by the new arising transmission scenario where primary data can be extended by a second, *supplementary data*, which is sent independently from a different source. We assume that the second stream revalues the primary one. In this case, injecting the supplementary data at suitable locations within the network is a crucial factor to lower the total network load.

The transmitted data consists of two parts: the pure payload traffic and extra sent data to cope with transmission errors. In the course of this paper we call the former type *primary* traffic and the latter type *redundancy*. The main objective of this work is to find a mechanism that reduces the amount of traffic whereas the operating conditions of the transmission and the connected applications are not disturbed. Specifically, we propose the way to lower the amount of redundancy since the primary traffic can be reduced only by applying more efficient source-coding mechanisms.

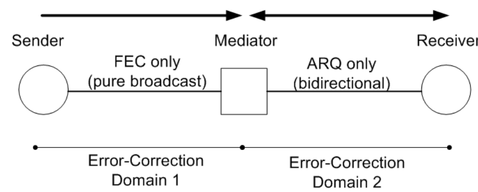

Fig. 1. Error-Correction Relay

III. Node Characteristics

Current networks evolve an increasing number of different physical transmission mechanisms as fiber and copper links, wireless LAN or 3G and 4G connections, resulting in highly heterogeneous topologies. In general network nodes serve as routers dealing with forwarding packets to the right next hop. Multi-purpose nodes are able to operate in different ways: as a *routing relay*, *error-correction relay*, and, *supplementary data injector*. Further we call such multi-purpose nodes *Mediators* following their operating principle of mediating traffic between multiple network segments.

A. Routing Relay

The first and simplest operation mode of Mediators is the *routing relay mode*. In this mode the node acts as a normal network router, simply forwarding the data packets to the right next hop that is closer to the designated destination of the data. In this case, no additional enhancements for the node are required. No additional complexity is introduced. Thus, all the existing network routers are operating in this mode. We assume *routing relay* is the default mode for Mediators.

B. Error-Correcting Relay

Mediator operating in the *error-correcting relay* mode splits the end-to-end transmission path into multiple segments. It enables a precise and individual application of error-correction schemes to the particular network sections. Thus, an explicit loss domain separation is established. This domain separation frees insusceptible links from traffic introduced by error-prone segments on the same path. The error-correction relay mode works with both pure broadcasting correction schemes as forward error correction (FEC) and bidirectional correction approaches as automatic repeat request (ARQ). A combination of both schemes to the hybrid error-correction (e.g. HEC [13]) is also conceivable, especially in case of time and residual loss restricted transmission conditions. In contrast to the aforementioned mode an error-correction relay requires more resources as CPU power and larger buffers for a reliable application of error protection techniques. The exact overhead depends on the specific error correction approach applied. Figure 1 presents a schematic application of two different error-correction schemes for two separated path segments, thus resulting in areas of individual error-correction domains on the path. Obviously, all the ARQ rounds do stress segment 2 only whereas segment 1 do not suffer from the extra needed rounds.

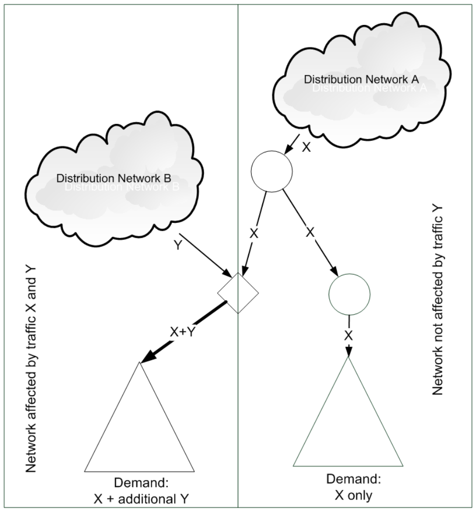

Fig. 2. Supplementary Data Injector

C. Supplementary Data Gateway

The *supplementary data gateway* mode does not modify the given network characteristics but constitutes a gateway to other networks. Mediator acting in this mode exploits the network topology and the availability of redundant transmission content. The gateway opens multiple additional transmission features.

We distinguish between *horizontal* and *vertical* supplementary data. The *horizontal* supplementary data refers to the traffic containing the same content but sent via other networks. An example for this type is live sports content which could also be sent via satellite or terrestrial propagation besides the IP transmission. We define *vertical* supplementary data as real additional data that revalues the primary data stream. An example of this traffic type could be a program information during an IPTV transmission for hearing-impaired people. Both supplementary data types are not supposed to be originated by the same source as the primary traffic.

Physical requirements for the *supplementary data gateways* mode are more distinctive as for the preceding modes. To inject supplementary data the node should be able to provide access to other networks via specific interfaces as DVB-S/T tuner for satellite or terrestrial reception. An important aspect is synchronization of the primary and supplementary data streams. The implementation must provide a way to ensure that both streams perfectly fit together in order to deliver a smooth experience at the receiver.

Figure 2 illustrates the operating principle of supplementary data injectors.

Mediator nodes are supposed to support one of the last two modes or both. The nodes are aware of their own operation modes and the modes of their neighbors.

Figure 3 presents a summary of all presented operation modes located within a simple tree network.

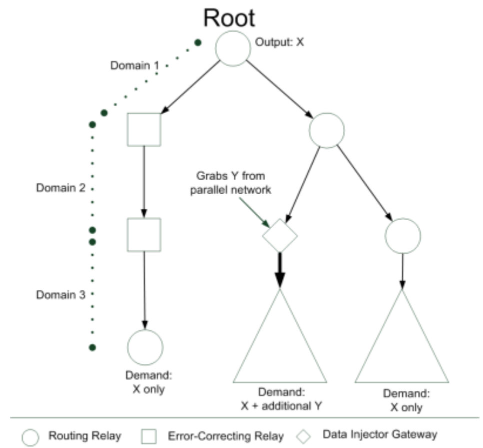

Fig. 3. Mediators' operation modes

IV. Node Location Assignment

Since the Mediator nodes actively influence transmission characteristics, a careful placement of these node within the dissemination structure is required. There are two possible scenarios: In first, the transmission structure is known a priori. In this case all participating nodes are already logically connected by a tree or mesh. In the second case, the transmission structure is not yet known. The dissemination structure can be built with consideration of the possible Mediator locations.

A. Metrics

In order to construct a dissemination structure an appropriate metric that reveals characteristics of the network segments is required.

Typically distribution mechanisms rely on Spanning Tree algorithms [12] that incorporate only one metric, e.g. minimum hop count. For instance, the Dijkstra algorithm uses the number of hops to find a feasible path through a network; the spanning tree algorithms of Kruskal and Prim also employ the number of hops between the sender and receiver. When dealing with elastic traffic, such as HTTP or FTP file transfers, the length of the transmission path should be minimized and therefore the number of hops is a sufficient decision criterion.

Multimedia live traffic implies an intrinsic time characteristics, and the length of a transmission path loses its significance, the delivery time and the residual loss probability are more important. Thus, finding an optimal network path does not rely on only one metric anymore. The decision space grows to two dimensions as depicted in figure 4: time and residual loss probability. Here C_{time} and C_{loss} represent the constraints that define the rectangular feasible constraint area. If two metrics are used, there is no global and unique ordering and therefore a combination of both metrics is desirable to map the two dimensional space to a one dimension. A more powerful metric which incorporates more information about the network could doubtlessly lead to a higher transmission gain. In the following, we review two mapping approaches proposed by DeNeve in [18].

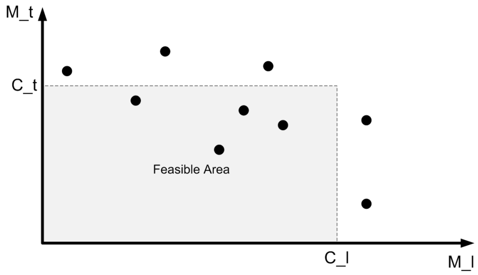

Fig. 4. Feasible Area

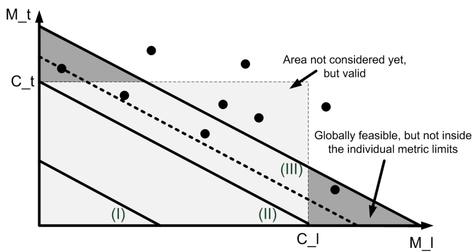

Fig. 5. Linear Mapping Approach

1) Linear Mapping: The very basic method of mapping two different metrics into one is to take their linear combination:

$$f(M_t, M_l) = w_t \cdot M_t + w_l \cdot M_l \in \mathbb{R}$$

where w_t and w_l are positive real numbers indicating weights of the time and loss probability metrics M_t and M_l. It can be easily seen that multiple inputs of M_t and M_l can result in the same metric value of $f(M_t, M_l)$.

Assume a fixed value $K = f(M_t, M_l)$. The equation above can be transformed to the form

$$f'(M_l) = M_t = -\frac{w_l}{w_t} \cdot M_l + \frac{K}{w_t}$$

Obviously, this mapping represents a strictly monotonically decreasing line. Figure 5 illustrates the issue that arises with the application of this mapping.

An algorithm (e.g. Dijkstra) which looks for a minimum metric value starts in the origin $f' = 0$. Then it shifts the line $f'(M_l)$ parallelly to the right until it hits a metric point. Figure 5 illustrates the case where the first hit is a point that lies outside of the feasible area but has the smallest value found so far (dashed-line). Thus, the search algorithm is unaware of the fact that the found entry is infeasible.

Ideally, the composite metric function should output the values that are within the feasible area. With the linear metric approach, the algorithm must stop shifting the line as soon as the line crosses the diagonal of the feasible area. Everything beyond this point can produce wrong decisions. In case the applied algorithm can not be adapted to check the feasibility of the metric outcome (e.g. since the algorithm source is not available), half of the feasible region could be left unscanned, reflecting the quality of the final results.

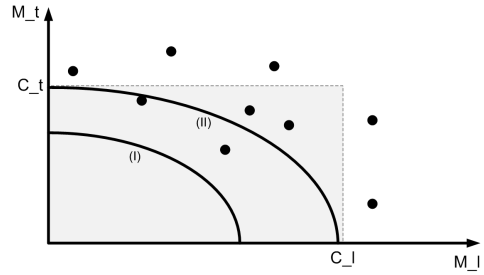

Fig. 6. Curved Mapping Approach

2) Curved Mapping: To reduce the size of the unscanned feasible area, the curved mapping method can be applied. We can define the mapping function as a Holders 2-vector norm [18]:

$$\mathbb{R} \ni f(M_t, M_l) = \sqrt{\left(\frac{M_t}{C_{time}}\right)^2 + \left(\frac{M_l}{C_{loss}}\right)^2}$$

With this mapping the feasible constraint value space is exploited better, as illustrated in Figure 6. Thus, more potential feasible metric values are scanned. The approach could also combine more than two metrics (e.g. bandwidth constraint can be easily added).

B. Location Assignment Algorithms

The location assignment process is highly important since it determines where the actual error-correction takes place or where additional data is injected from the parallel networks. The main objective of the location assignment is to establish an effective error-correction domain separation. Thus, an individual error-correction scheme tailored to the underlying physical conditions is applied on each network segment, leading to the reduction of overhead and improvement in the overall transmission procedure.

In the following the basic ideas of how to select suitable Mediator locations within the data dissemination network are presented and should serve as a general rule of thumb for the location selection process.

1) Network Topology Based Assignment: This approach assumes that the hardware of the network nodes is qualified to handle the additional operations without being overloaded. Potential positions for the Mediator nodes could be identified using the topological characteristics of the network nodes, such as the (weighted) degree, centrality or betweenness of individual network nodes [10]:

- **Degree:** The basic factor to determine how many adjacencies the node has is its degree. Obviously, the higher the degree the more connections to other node are available. This may lead to a definite occurrence in distribution tree structures. Thus, the degree of a node n_i with adjacency matrix x_{ij} is defined as

$$degree(i) = \sum_{j}^{N} x_{ij}$$

where N represents the total number of nodes.

- **Closeness:** Incorporating shortest-path measurements in the network lead to the closeness metric. Thereby, it is assumed that a larger path introduces more costs for interaction. The longer the paths to the other nodes, the smaller the metric value. The inverse of the sum of distances from one node n_i to all others is defined as the closeness centrality metric:

$$closeness(i) = \left[\sum_{j}^{N} d(i,j) \right]^{-1}$$

  where $d(i,j)$ represents the distance between two nodes n_i and n_j in terms of hops and N again reflects the total number of nodes.
- **Betweenness:** Combining the number of shortest paths between any two nodes and the number of these shortest paths that pass a node n_i leads to the betweenness metric. Again, the more paths exploit this node, the higher the metric value. Let sp_{jk} represent the total number of shortest paths in terms of hops and $sp_{jk}(i)$ denote the number of paths passing node n_i, it holds for the betweenness metric:

$$betweenness(i) = \frac{sp_{jk}(i)}{sp_{jk}}$$

Obviously, this list is not exhaustive and can be extended by more characteristics from graph theory or traffic engineering.

When the set of potential candidates for Mediator node positions have been chosen, the optimization algorithms could be applied. There are multiple assignment algorithms in the related literature, which could be applied for optimization of the Mediator nodes positioning. The choice of the algorithm depends highly on the dissemination network topology and optimization goals. Further we review several algorithms which we consider suitable for choosing the right locations for Mediator nodes.

Li et al. [23] proposed an algorithm for finding the optimal placement of multiple web proxies among potential sites the trees. The algorithm obtains the optimal solution for the tree topology using $O(N^3M^2)$ time. It works for the scenarios where the clients can request data only from the parent, but not sibling proxy. This model is applicable for the multicast multimedia data transmission within the tree dissemination networks as well.

In [20] a control node assignment algorithm algorithm was proposed, which finds the optimal number of error-correcting relays and their recommended placements within the multicast dissemination tree topologies in $O(NlogN)$ time. The objective is to optimize redundancy information introduced into the network when HEC is applied. This algorithm is directly applicable for Mediator nodes location when they perform in *error-correcting relay* mode.

For the general graph topologies a web server replicas placement model was proposed in Qiu et al. [17]. The authors formulated the problem as Minimum K-Median Problem, which is known to be NP-hard, and analyzed several approximation algorithms. They showed that a simple greedy approach, where the optimal locations for web replicas are chosen one by one according to the associated costs until M is reached, performs the best with the median performance within the factor 1.1-1.5 of optimal.

2) Subjective Assignment: The *Subjective Assignment* depends on a Mediator distribution concept, fully developed by an administrator without any direct reference to the actual network topology. Thus, the factors such as hardware capacity, financial considerations, customer's requirements or networking policies within the individual autonomous systems (AS) affect the selection. One must also take into consideration that network providers may deny the application of multi-purpose nodes at certain locations but enforce, even if the network characteristics do not match with the objective requirements.

Clearly, a combination of multiple assignment strategies to find suitable locations is also possible.

Additionally, in the following we share our considerations for the location assignment strategies applicable separately for each Mediator mode.

C. Routing Relay

In this mode a Mediator is acting as a basic router. Thus, no special requirement for placement is needed.

D. Error-Correction Relay

Establishing multiple error-correction domains within a transmission tree is the main objective when Mediators operate in the error-correction relay mode. Thus, not all possible locations within the tree are suitable. Insertion of the excessive Mediator nodes or their suboptimal positions can lead to a degradation of the overall performance and higher overhead. In this mode the most promising assignment method is position the Mediators at the nodes that connect highly inhomogeneous links [26]. These locations help to separate loss domain sections in the network by protecting network segments with lower error probabilities of being flooded with redundant data introduced by segments with higher loss probabilities.

Another intuition for proper location assignment is to assign Mediators to the nodes with large betweenness values since the error-correction relay can be reused by multiple paths.

E. Supplementary Data Gateway

This mode is suitable for the cases where primary data can be extended by supplementary information. Assume two groups of recipients: one has capabilities to receive a primary stream only whereas the second is able to increase the value of the received primary data by a set of secondary information. We assume that the distinction is implemented in the receiving device or subscription policies. In addition, both data types may not be originated at the same source. Obviously, the recipients with equal capabilities are to be grouped accordingly and, assigning Mediators for each group separately we release parts of the network from the burden of redundant data.

V. Example Application Scenarios

The proposed Mediator concept can be used with several already established mechanisms and improve their functionality (reliability, resource requirements, etc.). Here we present several example application scenarios, where Mediator nodes could be deployed incrementally to the existing networks in order to optimize their performance.

A. Content Delivery Networks

Content Delivery Network (CDN) is designed to avoid congested network segments, place the requested content closer to the receiver and improve the content delivery quality, speed and reliability while reducing the network load at the primary source server [14]. The main issues with CDNs are the placement of the surrogate servers, the selection of content and data synchronization. The CDN surrogate server can be seen as Mediator where 1) data is injected from a parallel network (e.g. DVB-T/DVB-S) to lower the data storage and synchronization effort while releasing parts of the network from carrying data to the receiver and 2) additional error-correction is applied to lower the amount of extra needed bandwidth in the network due to error-prone segments.

B. Dynamic Adaptive Streaming over HTTP (DASH)

Dynamic Adaptive Streaming over HTTP (DASH) [2] mainly addresses the HTTP-based progressive downloads mechanism, but also attempts the arising issues as missing bitrate adaptivity or waisted network bandwidth due to user terminated sessions while further content has been already downloaded [4]. Thus, the server holds a set of differently encoded media chunks and the receiver choses an appropriate bitrate, thereby changing the quality. To avoid congestion or overload sever farms (HTTP caches) are established, that allow highly scalable distribution scenarios. Introducing Mediators into this environment could help to improve the media retrieval process from the source server to the server directly communicating with the receiver: if content is not already available, a reliable and nearly real-time reloading from the source server is possible. Thus, the HTTP caches can be quickly refreshed in multicast mode if required.

C. Peer-to-Peer Networks

Traditional Peer-to-Peer Networks [15] are overlay networks, built above the physical or logical networks. The main challenge with peer-to-peer network is the high heterogeneity within the set of nodes and connections between the nodes (e.g. DSL, wireless, backbones, etc.). Recent approaches [7] already incorporate more information from the underlying physical network, but they focus mostly on the financial aspect but not on reliability and network speed. Introducing Mediators into peer-to-peer overlay networks helps to correct transmission errors due to highly error-prone communications links (e.g. IEEE 802.11) by individually protecting these weak links with a better error-correction code, which leads to a lower network utilization when using additional supplementary data injector. Mediator creation within an overlay network causes minimal additional setup effort.

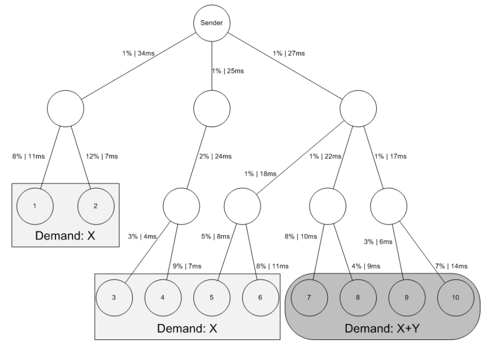

Fig. 7. Networking Example

VI. Experimental Example

In the following we provide an artificial example to demonstrate the benefits achieved by applying multi-purpose Mediator nodes in the networks with tree shape.

We assume an upper limit for delivery of $150ms$ for each receiver and a maximum residual error rate of 10^{-6} for each link.We assume tree with one sender and ten receivers $R_i,\ 1 \leq i \leq n_p = 10$ as depicted in Figure 7. Thus, the for the set of nodes holds $|V| = 10$ and for the set of edges holds $|E| = 17$. The source at the root of the tree sends data traffic X with a rate of $4MBit/s$. That is, in case no error-correction scheme is applied, the average total unicast network load T_{ref}^{uni} is

$$T_{ref}^{uni} = \frac{\sum_{j=1}^{n_p} l_j \cdot 4MBit/s}{|E|} = 6.58MBit/s$$

where l_j equals the length of path j. The link characteristics - round-trip time rtt_i and packet loss probability p_i are given in the figure. The closer links are to the leaves, the higher the loss probabilities are assigned to simulate error-prone links (e.g. wireless LAN). The links closer to the sender have larger round-trip times and lower error probabilities, which reflects the stable but large distribution network parts.

Firstly, we calculate the average amount of redundancy required in a theoretical end-to-end case with unlimited delivery time for each path to a receiver. The results RI_{theo}^{e2e} are presented in Table I. We define the average amount of redundancy in the network in unicast end-to-end case as

$$\bar{RI}_{theo}^{e2e} = \frac{\sum_{j=1}^{n_p} l_j \cdot \frac{p_j^{e2e}}{1-p_j^{e2e}}}{|E|} \approx 0.1523$$

where p_j^{e2e} denotes the end-to-end error probability on the path j, and l_j is the length of path j. Thus, the average total network load T_{theo} is

$$T_{theo}^{e2e} = \frac{\sum_{j=1}^{n_p} l_j \cdot 4 \cdot (1 + \bar{RI}_{theo}^{e2e})}{|E|} = 7.59MBit/s.$$

Secondly, we consider an unicast end-to-end scenario and calculate the amount of required redundancy if the *adaptive hybrid error correction (AHEC)* framework proposed in [8] is used with the constraints defined in the beginning of this section. The sender establishes an individual communication

TABLE I
OVERVIEW OF THE ERROR-CORRECTION RELAY RESULTS UNDER CONSIDERATION OF STRICT DELIVERY CONSTRAINTS

	RI^{e2e}_{theo}	RI^{e2e}_{AHEC}	RI^{relay}_{AHEC}
Path 1	0.0970	0.1210	0.0491
Path 2	0.1478	0.1539	0.0747
Path 3	0.0626	0.0693	0.0602
Path 4	0.1327	0.1857	0.0942
Path 5	0.0740	0.0879	0.0562
Path 6	0.1090	0.1370	0.0738
Path 7	0.1090	0.2251	0.0738
Path 8	0.0628	0.1501	0.0507
Path 9	0.0519	0.0566	0.0453
Path 10	0.0971	0.2072	0.0747
Network RI average	0.1523	0.2298	0.1077
Traffic [MBit/s]	7.59	8.10	7.30

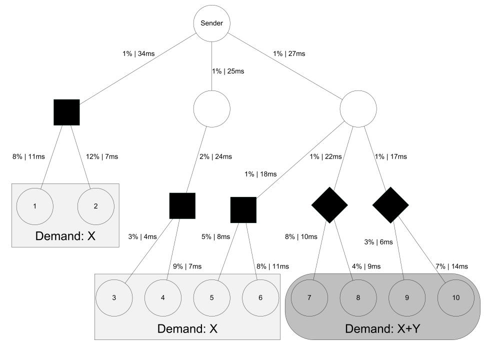

Fig. 8. Error-correction relay example

channel for each receiver R_i. The results for RI^{e2e}_{AHEC} values are presented in Table I. The average total amount of load in the network when applying an end-to-end AHEC scheme is given by:

$$\bar{RI}^{e2e}_{AHEC} = \frac{\sum_{j=1}^{n_p} l_j \cdot RI^{e2e}_{AHEC}(j)}{|E|} \approx 0.2298$$

where $RI^{e2e}_{AHEC}(j)$ reflects the redundancy calculated with the AHEC framework, that is using both optimized FEC and ARQ mechanisms, for the end-to-end scenario. As you can see $\bar{RI}^{e2e}_{AHEC} \geq \bar{RI}^{e2e}_{theo}$ since AHEC considers the strict time limit of $150ms$ in contrast to the theoretical case. Thus more redundancy must be used to correct errors down to a residual error-rate of 10^{-6}. Thus, the average total network load T^{e2e}_{AHEC} is

$$T^{e2e}_{AHEC} = \frac{\sum_{j=1}^{n_p} l_j \cdot 4 \cdot (1 + \bar{RI}^{e2e}_{AHEC})}{|E|} = 8.10 MBit/s.$$

Further we consider a multicast transmission with AHEC. The virtually worst receiver $\tilde{R}$ among all R_i is used to calculate the required error-correction redundancy. The globally longest round-trip time and highest packet loss probability are combined and assigned to $\tilde{R}$. This guaranties that all receiver-paths are served with a sufficient protection. In this scenario, $\tilde{R}$ has a round-trip time of $59ms$ from R_7 and a packet loss probability of 12.88% from R_2.

Since in multicast all links carry the same amount of data, for the average network load holds

$$\bar{RI}^{mc}_{AHEC} = RI^{mc}_{AHEC}(j) \approx 0.2899, \text{for all j}$$

Thus, the total network load T^{mc}_{AHEC} on average is

$$T^{mc}_{AHEC} = 4 \cdot (1 + \bar{RI}^{mc}_{AHEC}) = 5.16 MBit/s.$$

Obviously, $T^{mc}_{AHEC} < T^{e2e}_{AHEC}$ which confirms that multicast transmission helps to save network load. Unfortunately, it is not widely used in the open Internet environment and thus it serves more as a reference value.

Next, we consider the case then each end-to-end path is split into two end-to-end segments. A coding relay is inserted just before the receivers. We are segmenting the network according to its physical properties. Figure 8 presents the locations of the error-correction relays as shaded nodes and thus illustrates this split. The overall time limit is bounded to $150ms$. We explicitly distribute the coding time budget in a robust proportion of $2:1$ among the segments to allow at least multiple ARQ rounds. Thus, the segment closer to the sender has $100ms$ to perform error-correction, and the one closer to the receiver has $50ms$. We calculate $RI^{e2e}_{AHEC,[1,2]}$ for each path and each segment of the path, and estimate the mean $RI^{relay}_{AHEC} = 0.5 \cdot (RI^{e2e}_{AHEC,1} + RI^{e2e}_{AHEC,2})$ for each path. The results are also presented in Table I.

The average total amount of load in the network when applying a two-segment relay AHEC scheme for each receiver in unicast is given by:

$$\bar{RI}^{relay}_{AHEC} = \frac{\sum_{j=1}^{n_p} l_j \cdot RI^{relay}_{AHEC}(j)}{|E|} \approx 0.1077$$

where $RI^{relay}_{AHEC}(j)$ reflects the redundancy calculated with the AHEC framework in a two-segment AHEC scenario of path j and l_j equals the length of path j.

We observe that after the insertion of only one Mediator per path already leads to a lower average redundancy in the network in comparison to the end-to-end transmission, which is lower than the theoretical value for the end-to-end scenarios.

Thus, the average total network load T^{relay}_{AHEC} is

$$T^{relay}_{AHEC} = \frac{\sum_{j=1}^{n_p} l_j \cdot 4 \cdot (1 + \bar{RI}^{relay}_{AHEC})}{|E|} = 7.30 MBit/s.$$

To complete this overview the multicast scenario with relays must also be considered. Therefore, we divide the network into multiple multicast areas mc_j. For each mc_j the virtually worst receiver $\tilde{R}$ is determined and used to calculate the AHEC configuration and the resulting redundancy $RI^{relay,mc}(j)$. Here, $q = 6$ six multicast areas are given: one large (root to relays) and five small (relays to their connected receivers).

Then, the average total amount of load in the network is given by:

$$\bar{RI}^{relay,mc}_{AHEC} = \frac{\sum_{j=1}^{q} s_j \cdot RI^{relay,mc}_{AHEC}(j)}{|E|} \approx 0.0963$$

where s_j equals the number of links in mc_j.

Thus, the average total network load T_{AHEC}^{relay} is

$$T_{AHEC}^{relay,mc} = \frac{\sum_{j=1}^{q} s_j \cdot 4 \cdot (1 + \bar{RI}_{AHEC}^{relay,mc})}{|E|} = 7.22MBit/s.$$

At the end we evaluate the effectiveness of the Mediator nodes insertion when when they act as supplementary data gateways. We assume the gateways have access to all required information and parallel networks. Figure 7 shows that receivers 7-10 have a demand for both traffics, X and Y, where Y serves as a supplementary information to revalue data X. The two gateways are located as close as possible to the group of receivers with double demands. Figure 8 illustrates this scenario where the rhombic shaped nodes denote the gateway locations only. Since both gateways grab the required content from a parallel network and inject it into the network only the lower four links, directly connecting them to the receivers, are influenced by a higher traffic due to additional demand Y.

In case of a traditional unicast transmission scenario the root is establishing a separate connection to each receiver and sending additional data Y. Let us define $\hat{V}$ with $|\hat{V}| = \hat{n}_p$ as the set of receivers demanding the additional stream. In this scenario the average total network overhead ΔT is

$$\Delta T = \frac{\sum_{j=1}^{\hat{n}_p} l_j \cdot 4Mbit/s}{|E|} = 2.82MBit/s.$$

In contrast, ΔT will decrease significantly as soon as the gateways start inserting the data at a positions closer to the receivers:

$$\Delta T = \frac{\sum_{j=1}^{\hat{n}_p} l_j \cdot 4Mbit/s}{|E|} = 0.94MBit/s$$

where $l_j = 1$ for all paths j from the gateway to the receiver.

VII. Conclusions

This paper proposes an evolutionary networking approach that has a potential to lower the required resources for multimedia applications. We propose to reduce the redundancy introduced into the system with error correction by tailoring error-correction schemes to both their application scope and underlying network topology, and furthermore, exploiting parallel networks for selective supplementary data insertion.

Experimental evaluation supports the concept by confirming that even a relatively small distribution network could significantly benefit from the insertion of several Mediator nodes acting in different operation modes adjusted according to the application requirements. In addition, sample metrics are provided that help to select suitable positions for *Mediators* within the large distribution trees. A feasible approach is discussed that enables multi-constraint multimedia applications, such as live IPTV, to use legacy networking algorithms that are designed to use only one objective value. Therefore, it is possible to find the global optimum routes within the network by bridging legacy algorithms with new arising multimedia applications.

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