Capillary multi-path routing with Forward Error Correction

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Abstract

Packetized communications over internet behave like erasure channels and the erasure resilient FEC codes can be applied on the packet level to combat packet losses.

For numerous packetized off-line applications, employment of erasure resilient codes offered spectacular results: in satellite feedback-less broadcasts of recurrent voluminous updates of GPS maps to millions of motor vehicles under the conditions of arbitrary fragmental visibility using Raptor codes [Shokrollahi04]; in a film industry for a fast delivery over Internet of the day's film footage from the location it has been shot to the studio that is many thousand miles away using LT codes [Luby02].

Off-line streaming benefits from application of FEC because, contrary to the real-time streaming, the application is not obliged to deliver in time the "fresh" packets of a very short life time and the buffer size is not a concern. If the buffering time must be maintained short, FEC can only mitigate short granular failures. Many studies reported weak or negligible improvements from application of FEC to real-time streaming [Johansson02], [Huang05], [Padhye00] and [Altman01].

FEC however can still improve significantly the tolerance of real-time streaming but we must exploit other dimensions which can "replace" the long buffering time. Studies stressing on the poor FEC efficiency always assumed that the media stream follows a single path. The second orthogonal ax to the buffering, to be exploited, is the underlying network routing. There is an emerging body of a literature addressing the advantages of multi-path routing in media streaming and suggesting the important and promising impact the routing can have to the efficiency of FEC [Qu04], [Tawan04], [Ma03], [Ma04], [Nguyen02] and [Nguyen03]. However these studies proved only the advantageousness of path diversity versus single path routing. The considered topologies and routing patterns in these papers are simple and are limited to only two alternate paths or in the best case to a sequence of parallel and serial links. The first step in path diversity, that is converting a single path routing to the basic multi-path routing, is not however the terminal achievement of the multi-path approach. There is lack of a work in the literature studying the routing as a space of possibilities and seeking in there the optimal point of FEC efficiency.

In this paper we try to present a comparative study across a wide range of friendly, all multi-path routing patterns virtually erected along a routing ax. Single path routing, being considered as too hostile, will be even excluded from our comparison system.

As an approach to multi-path routing concept we propose a family of *capillary routing*, which can be best defined by describing the iterative process transforming a simple single-path flow into a capillary route. In capillary routing the alternate paths are discovered by delegating the load of a single path route to other links. The load balance is reached by minimizing the upper bound value of the flow for all links. In the first layer the full mass of the flow is broken across a few parallel routes. By maintaining the flow below the upper bound obtained in the first layer, further equilibration is being applied to the remaining portion of the flow by minimizing the value of the upper bound of the second layer applied to all links except the bottlenecks of the previous layer. The objective of the second iteration leads to the sub-routes and the sub-bottlenecks of the second layer. The second layer's upper bound is added as an additional constraint (always maintaining the first constraint) and the construction of the successive layers is continued until the entire footprint of the flow is discovered and completely equilibrated. A flow traversing a large network with hundreds of nodes may usually have hundreds of capillary routing layers. Contrary to the shortest path or max-flow routing, capillary routing is unique for a specified source and destination. This paper presents the Linear Programming model for computing the capillary routing. At each layer of the capillary routing the flow represents a suggestion of a routing pattern and is a subject of evaluation (toward the FEC efficiency).

To compare two multi-path routing suggestions, we are introducing a measure of the routing's advantageousness. The cooperativeness or friendliness of a routing toward FEC is measured based on the satisfaction level of a realistic application employing end-to-end adaptive FEC. A temporary congestion or a failure of one of the links of the multi-path routing will produce random losses during the failure time. The packet loss rate observed at the receiver corresponds to the portion of the traffic being still routed toward the faulty route. The real-time media stream is usually equipped with a permanent tolerance to a certain constant level of packet losses (e.g. passive error concealment). VOIP for example can tolerate about 9% of packet losses, the permanent tolerance can be also obtained or increased by incorporating constantly a proper amount of FEC. If the losses measured at the receiver are about to exceed the critical tolerable level the receiver demands the sender via a feed-back channel for an increased rate of extra redundancy to be transmitted. The sender must stream a sufficient quantity of redundancy to compensate the new losses signaled by the receiver maintaining thus the communication at the required level of quality. The sender must compute the redundancy need, the new FEC block size FEC_p, as a function from the percentage of packet losses p reported by the receiver. FEC_p function is computed assuming Reed-Solomon encoder taking into account the desired decoding failure probability (10^{-5} in our measurements) and the number of media packets in the FEC block (10 or 20 packets). Adjustable FEC in real-time streaming was already proposed for implementation in practice by several other authors [Kang05], [Xu00], [Padhye00], [Johansson02] and [Huang05]. Although the proposed end-to-end adaptive FEC mechanism is not aware of the underlying routing and is implemented entirely in the application level of the end nodes, we define the total amount of the adaptive redundancy demanded from the sender during the communication time as a measure of the friendliness and advantageousness of the underlying network routing toward fault-tolerance.

We call this measure as Adaptive Redundancy Overall Need (ARON) strictly defined as the sum of all FEC overheads

demanded from the sender for the compensation of sequential losses of all sub-flows carried by each individual link in the footprint of the communication path. Let M be the initial number of original media packets to be delivered to the receiver by the transmission blocks. Let $FEC_p \geq M$ be the needed size (number of packets) of the transmission block, under $0 \leq p < 1$ percent of random losses in the network (observed at the receiver) for maintaining the required QoS. Let L be the set of links laying on the communication path, and let $r(l)$ be the load of a link $l \in L$ under the present routing scheme. Let the percentage $0 \leq t < 1$ of recoverable losses, be the level of the tolerance permanently maintained in the media stream (even if there are no losses). The equation for ARON then looks as follows:

$$ARON = \sum_{l \in L \,|\, t \leq r(l) < 1} \frac{FEC_{r(l)} - FEC_t}{FEC_t}$$

Under Shannon capacity assumption:

$$ARON = \sum_{l \in L \,|\, t \leq r(l) < 1} \left(\frac{1-t}{1-r(l)} - 1 \right)$$

To evaluate the friendliness of the capillary routing toward tolerant media streaming we measure ARON rating for each layer of capillary routing. Our study has shown that in scope of multi-path routing, significant improvement can be still obtained by improving the basic path diversity provided by the first layer of the capillary routing (i.e. the max-flow solution) toward more elaborated multi-path routing strategies provided by deeper layers of the capillary routing. Multi-path routing ax, similarly to the buffering ax, can also significantly burst the efficiency of FEC.

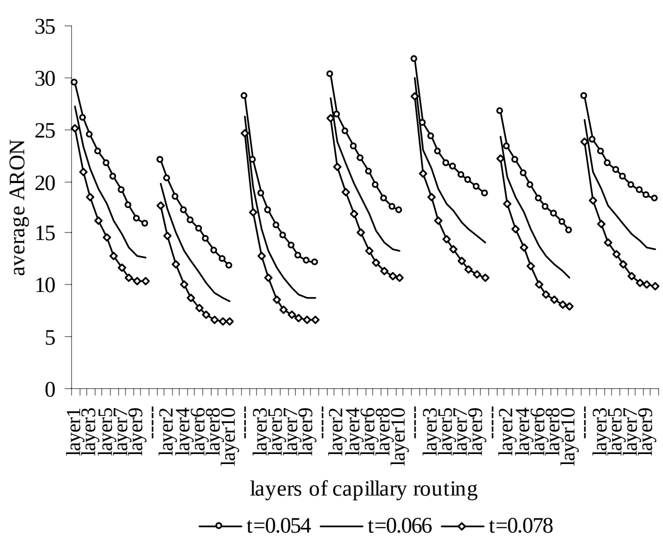

Fig.1. Adaptive Redundancy Overall Need as a function from the capillary routing layer

The chart of Fig.1 shows improvement of the ARON rating (i.e. reduction of the failure compensation overall cost) as the capillary routing layer increases. The chart represents 300 network samples (divided in 7 groups) obtained from a random walk Mobile Ad-hoc Network (MANET) with 115 nodes. Three curves correspond to media streams with 5.4%, 6.6% and 7.8% of the proper tolerance to packet losses.

References:

[Altman01] Eitan Altman, Chadi Barakat, Victor M. Ramos, “Queueing analysis of simple FEC schemes for IP telephony”, Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM 2001, Volume 2, April 22 – 26, pages 796 – 804

[Huang05] Yicheng Huang, Jari Korhonen, Ye Wang, “Optimization of Source and Channel Coding for Voice Over IP”, Multimedia and Expo 2005, ICME’05, July 06, pages 173 – 176

[Johansson02] Ingemar Johansson, Tomas Frankkila, Per Synnergren, “Bandwidth efficient AMR operation for VoIP”, Speech Coding 2002, IEEE Workshop, October 6 – 9, pages 150 – 152

[Kang05] Seong-ryong Kang, Dmitri Loguinov, “Impact of FEC overhead on scalable video streaming”, ACM Network and Operating System Support for Digital Audio and Video 2005, NOSSDAV’05, June 12 – 14, pages 123 – 128

[Luby02] Michael Luby, “LT codes”, The 43rd Annual IEEE Symposium on Foundations of Computer Science 2002, FOCS’02, November 16 – 19, pages 271 – 280

[Ma03] Rui Ma, Jacek Ilow, “Reliable multipath routing with fixed delays in MANET using regenerating nodes”, 28th Annual IEEE International Conference on Local Computer Networks 2003, LCN’03, October 20 – 24, pages 719 – 725

[Ma04] Rui Ma, Jacek Ilow, “Regenerating nodes for real-time transmissions in multi-hop wireless networks”, 29th Annual IEEE International Conference on Local Computer Networks 2004, November 16 – 18, pages 378 – 384

[Nguyen02] Thinh Nguyen, Avideh Zakhor, “Protocols for distributed video streaming”, Image Processing 2002, Volume 3, June 24 – 28, pages 185 – 188

[Nguyen03] Thinh Nguyen, P. Mehra, Avideh Zakhor, “Path diversity and bandwidth allocation for multimedia streaming”, Multimedia and Expo 2003, ICME’03 Volume 1, July 6 – 9, pages 663 – 672

[Padhye00] Chinmay Padhye, Kenneth J. Christensen, Wilfrido Moreno, “A new adaptive FEC loss control algorithm for voice over IP applications”, Performance Computing and Communications Conference 2000, IPCCC’00, February 20 – 22, pages 307 – 313

[Qu04] Qi Qu, Ivan V. Bajic, Xusheng Tian, James W. Modestino, “On the effects of path correlation in multi-path video communications using FEC over lossy packet networks”, Global Telecommunications Conference 2004, IEEE GLOBECOM’04 Volume 2, November 29 – December 3, pages 977 – 981

[Shokrollahi04] Amin Shokrollahi, “Raptor codes”, International Symposium on Information Theory 2004, ISIT’04, June 27 – July 2, page 36

[Tawan04] Tawan Thongpook, “Load balancing of adaptive zone routing in ad hoc networks”, TENCON 2004, Volume B, November 21 – 24, pages 672 – 675

[Xu00] Youshi Xu, Tingting Zhang, “An adaptive redundancy technique for wireless indoor multicasting”, Fifth IEEE Symposium on Computers and Communications 2000, ISCC 2000, July 3 – 6, pages 607 – 614