Cross-Layer Optimization with Real-Time Adaptive Dynamic Spectrum Management for Fourth Generation Broadband Access Networks

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Abstract. The upcoming fourth generation of broadband access systems (4GBB) needs to address data rates of up to 1 Gbit/s over twisted-copper pairs. Physical layer techniques like dynamic spectrum management (DSM) aid in increasing the data rate by optimizing the space and frequency domain. However, there is room for improvement in the time dimension that both physical and upper layers can use to their advantage. This paper proposes a bidirectional cross-layer approach to optimize DSM using techniques like scheduling and statistical multiplexing, to mitigate crosstalk, the dominant cause of signal degradation. This in turn should lead to better data rates, more stable networks, and "greener" devices.

1 Introduction

Driven by the emergence of evermore requiring broadband services such as e-business, cloud computing, IPTV and video-conferencing the needs for reliable and fast broadband internet access has become essential to life quality, efficiency and organizations. Quality of service (QoS) requirements for these applications become quite challenging, and thus it is important to improve broadband technologies.

The intermediate step to a global fiber-to-the-home (FTTH) instalment, is the hybrid fiber – copper telephone wires, using the existing telephony DSL infrastructure for the so called *last mile*, identified as the fourth generation broadband (4GBB) access network [12, 2].

Increasing VDSL2's datarates (of up to 100 mbit/s) to 1 Gbit/s over these copper wires proves a significant challenge. One of the wireline techniques used to boost data rates is dynamic spectrum management (DSM) [13]. DSM is developed as a means to solve the crosstalk problem. As twisted-copper pairs of different users are merged inside large cable bundles, electromagnetic coupling between neighbouring pairs leads to signal leakage in other users' signals. This is called cross-talk, and is currently the major cause of performance degradation in DSL transmission [4, 18].

Despite the word *dynamic* in DSM, the configuration remains static over time. And thus the time-domain is left unexploited. As the worst-case scenario is envisioned, the settings are very conservative and there is much to gain by taking this dimension into account.

Therefore, we investigate the concept of real-time adaptive DSM, which takes the short time-scale changing environment and requirements into account when calculating the power configuration. This leads to new mechanisms to improve transmission, energy efficiency (e.g. using low-power modes), and stability of the overall network.

However, the physical layer does not have the information that allows for this real-time adaptation and the upper layers could optimize more using physical layer information, hence the need for a cross-layer approach. Cross-layer refers to the exchange of knowledge between layers of the Open Systems Interconnection (OSI) model [1], a layered abstraction of the networking protocol stack (e.g. [14])

In our envisioned model there is a mutual influence between the physical layer and the upper layers (layer two and up). For example, telephony requires a very reliable and constant bit rate (CBR), while web traffic is of highly bursty nature, can cope with loss but needs to be responsive, and background traffic has high bandwidth requirements but does not suffer from delays. This valuable upper layer information can steer the physical layer into assigning three channels with different data and bit-error rates. The physical layer in its turn can report crosstalk, or share common time-frequency slots with other users, to which the upper layers, such as the scheduler, can make decisions.

The goal of this research is the development of a bidirectional cross-layer real-time adaptive DSM optimization framework for mitigating crosstalk by exploiting the time-dimension.

2 Approach

In this research we will investigate the upper layers and work in close collaboration with a researcher that looks at the physical layer optimizations.

The first step in tackling the problem consists of defining a framework with scope, and constructing a multi-layer system model that allows for cross-layer optimization. It includes determining the degrees of freedom and mechanisms, parameters and metrics that can be used for uni- or bidirectional cross-layer optimization.

Metrics of interest include the delay, delay variation, loss, Quality of Experience (QoE), power usage and retransmission probability. Not all metrics will apply for all traffic. E.g. some traffic does not suffer from large delay variation.

Most literature considers a unidirectional information exchange. Linking the several layers with a bidirectional channel results in new possible optimizations. This increase of degrees of freedom might result in unmanageable complexity. Restricting parameters or the degrees of freedom help in handling this. Determining the optimal power configuration, for example, is exponential in complexity

[16]. Limiting the update frequency and set of possible bandwidths can alleviate this.

Upstream and downstream have to be treated differently: the latter can be managed centrally as all information is readily available. The upstream traffic, on the other hand, can not be coordinated locally, and thus information exchange with the central office has to be taken into account.

The second phase will focus on the development of a cross-layer optimization approach for the system model.

Main topics of interest here for the upper layer are scheduling and statistical multiplexing. Statistical multiplexing is the merging of several flows such that the required bandwidth is less than the sum of the required bandwidths of the individual flows. Huang [8] shows that this can lead to impressive performance gains in cross-layer settings. Multiplexing has to be considered in a centralized cross-layer setting taking all users into account as there is a positive correlation between crosstalk and data rates in a cable bundle. Furthermore, predicting data and channel behaviour over a short time horizon can enhance the allocation of physical resources and allow for using low power modes, such as stable sleep [10].

The final step comprises a complete and realistic 4GBB simulator with cross-layer optimizations. Using realistic stochastic and worst-case channel models it will be possible to evaluate QoS performance statements, and identify constraints related to the time dimension such as delay, delay variation, retransmission probability and overhead of the upstream communication. The simulation will then be used to compare different scenarios against the G.fast standardization [9].

3 Current State

The current model consists of four building blocks: the application manager, the scheduler, admission control and operational controller. They are depicted in Figure 1 together with possible interactions and an example frequency-time slot mapping, the configuration of bits on the wire.

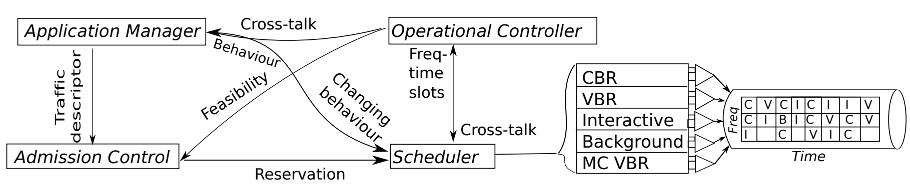

Fig. 1. Model, interactions and frequency-time slot mapping

Upon a new flow requesting access, the application manager translates this request to a long term traffic descriptor, and probes the admission control for a suitable physical layer configuration. If found the scheduler is updated to support the new flow. The scheduler selects packets for transmission for each traffic class (of which there are high reliability CBR, high reliability VBR, interactive traffic, background and multicast VBR). Each of these packets is then mapped to a time-frequency slot, guided by the operational controller. The operational controller uses convex programming to minimize power usage and maximize the frequency-time slot assignment in function of application requirements over all users.

4 Related Work

Previous research is mainly focused on unidirectional cross-layer optimization. For example [3] takes channel state and queue length into account to schedule for optimal throughput. However, the physical layer does not take any of the upper layers' information into account.

Most literature dealing with cross-layer optimization can be found in the wireless network area [3, 17, 6, 11, 7, 15]. Approaching DSL as a multi-user system, rather than isolated wires, results in similarities between wireless and DSL, and hence allows us to make use of these results. They are different enough (e.g. mobility, MAC, hidden terminal problem ...) that results can not be used directly.

Cross-layer design, such as [11, 6], focuses on the principles of decomposition and will be of value for our research.

Relating to the second phase, Çiftçioğlu [3] proposed a predictive block scheduler for a wireless system model. Our aim is to improve this model for a wired setting and provide a more general cross-layer framework.

In contrast to other literature, the FAST copper project [5] focuses on improving DSL. It considers four dimensions: frequency (physical layer allocation), amplitude (shaping at edge), space (network architecture and topology) and time (multiplexing). Whereas FAST focuses on optimizing network performance, we will optimize only the last mile by exploiting the time dimension (scheduling, multiplexing, traffic prediction), and focusing on the QoE.

5 Preliminary Conclusions and Future Work

This paper presented an approach to developing a cross-layer optimization with real-time adaptive DSM for 4GBB. Incorporating the time dimension, mechanisms like scheduling and statistical multiplexing will allow us to mitigate crosstalk, a major source of signal degradation, leading to better data rates, greener devices and more stable networks.

Future work will focus on a more tight collaboration of the physical layer and upper layers, iterative upgrading of the framework and performing simple simulations to evaluate metrics, continuing along the path as in section 2.

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References

1. Bertsekas, D.P., Gallager, R.G., Humblet, P.: Data networks, vol. 2. Prentice-Hall International (1992)
2. van den Brink, R.F.: Enabling 4gbb via the last copper drop of a hybrid ftth deployment. Broadband, Journal of the SCTE 33(2), 40–46 (2011)
3. Çiftçioğlu, E.N., Gürbüz, Ö.: Scheduling for next generation wlans: filling the gap between offered and observed data rates. Wireless Communications and Mobile Computing 11(5), 654–666 (2011)
4. Cendrillon, R., Moonen, M., Verlinden, J., Bostoen, T., Ginis, G.: Improved linear crosstalk precompensation for dsl. In: Acoustics, Speech, and Signal Processing, 2004. Proceedings.(ICASSP'04). IEEE International Conference on. vol. 4, pp. iv–1053. IEEE (2004)
5. Chiang, M., Huang, J., Cendrillon, R., Tan, C.W., Xu, D.: Fast copper for broadband access. In: Optics East 2006. pp. 639003–639003. International Society for Optics and Photonics (2006)
6. Chiang, M., Low, S.H., Calderbank, A.R., Doyle, J.C.: Layering as optimization decomposition: A mathematical theory of network architectures. Proceedings of the IEEE 95(1), 255–312 (2007)
7. Fu, F., van der Schaar, M.: Decomposition principles and online learning in cross-layer optimization for delay-sensitive applications. Signal Processing, IEEE Transactions on 58(3), 1401–1415 (2010)
8. Huang, J., Tan, C.W., Chiang, M., Cendrillon, R.: Statistical multiplexing over dsl networks. In: INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE. pp. 571–579. IEEE (2007)
9. ITU-T: Recommendation itu-t g.9701 - fast access to subscriber terminals (g.fast) - physical layer specification (2014)
10. Kamitsos, I., Tsiaflakis, P., Ha, S., Chiang, M.: Stable sleeping in dsl broadband access: Feasibility and tradeoffs. In: Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE. pp. 1–6. IEEE (2011)
11. Lin, X., Shroff, N.B., Srikant, R.: A tutorial on cross-layer optimization in wireless networks. Selected Areas in Communications, IEEE Journal on 24(8), 1452–1463 (2006)
12. Odling, P., Magesacher, T., Host, S., Borjesson, P.O., Berg, M., Areizaga, E.: The fourth generation broadband concept. Communications Magazine, IEEE 47(1), 62–69 (2009)
13. Song, K.B., Chung, S.T., Ginis, G., Cioffi, J.M.: Dynamic spectrum management for next-generation dsl systems. Communications Magazine, IEEE 40(10), 101–109 (2002)
14. Srivastava, V., Motani, M.: Cross-layer design: a survey and the road ahead. Communications Magazine, IEEE 43(12), 112–119 (2005)
15. Van Der Schaar, M., et al.: Cross-layer wireless multimedia transmission: challenges, principles, and new paradigms. Wireless Communications, IEEE 12(4), 50–58 (2005)
16. Vangorp, J., Tsiaflakis, P., Moonen, M., Verlinden, J., Van Acker, K.: Optimal spectrum balancing in multi-user xdsl systems with on/off power loading. In: Acoustics, Speech and Signal Processing, 2006. ICASSP 2006 Proceedings. 2006 IEEE International Conference on. vol. 4, pp. IV–IV. IEEE (2006)
17. Yu, W., Kwon, T., Shin, C.: Multicell coordination via joint scheduling, beamforming and power spectrum adaptation. In: INFOCOM, 2011 Proceedings IEEE. pp. 2570–2578. IEEE (2011)

18. Zeng, C., Aldana, C., Salvekar, A.A., Cioffi, J.M.: Crosstalk identification in xdsl systems. Selected Areas in Communications, IEEE Journal on 19(8), 1488–1496 (2001)