A Holistic Classification to the Study of Optical Interconnection Networks

Brian J. d'Auriol
Department of Mathematics and Computer Science
The University of Akron
Akron, Ohio, U.S.A. 44325-4002

Abdullah Abonamah
Department of Mathematics and Computer Science
The University of Akron
Akron, Ohio, U.S.A. 44325-4002

Abstract ***A classification of the related areas of optical/optoelectronic interconnection network research, electrical-based interconnection network research and computational models is presented. In particular, a holistic viewpoint of optical/optoelectronic interconnection networks is adopted. This viewpoint provides significant insight into the important issues regarding optical/optoelectronic interconnection network research, and more importantly, its role in supporting teraflop computing. In particular, relationships between these three areas are characterized. Two types of relationships have been considered: electrical-to-optical and computational-to-optical.***

Keywords: Optical/Optoelectronic, Interconnection Networks, Computational Models.

1 Introduction

The recent intensified research efforts in the area of optical and optoelectronic interconnection networks have been motivated by the desire to attain significant increases in computational speed, in the order of teraflop (or beyond) computing. The prevailing view in the research community is that such a goal is realizable only by the deployment of optical-based interconnection networks in high performance computing systems [1, 2, 3]. There is a wide spectrum of research interests in current interconnection networks. Advancements in physical optical technologies for transport, architecture, media access protocols, intelligent optical networks and models for computations are noted in the recent literature [3].

We note that there are significant relationships between optical-based interconnection network research and its electrical-based counterpart. Many communication protocols and topologies from the electrical domain have been modified and extended to produce better optical/optoelectronic networks [2, 4, 5, 6].

We also note that some new fast algorithms have been proposed for optical/optoelectronic architectures [1, 7, 8]. It is clear that optical/optoelectronic networks have a profound impact on the speed of computations.

In this paper, we provide a classification of the related areas of optical-based interconnection network research, electrical-based interconnection network research and computational models. In particular, we adopt a holistic viewpoint of optical interconnection networks. This viewpoint provides significant insight into the important issues regarding optical interconnection network research, and more importantly, its role in supporting teraflop computing. In particular, we characterize the relationships between these three areas, namely, electrical-based interconnection network research, optical-based interconnection network research and computational models.

This paper is organized as follows. A holistic viewpoint of optical-based interconnection network research, electrical-based interconnection network research and computational models is presented in Section 2. This discussion focuses on the nature and roles of the significant relationships between the three domains. Section 3 examines further details pertaining to the relationships between electrical-based interconnection network research and optical-based interconnection network research as well as between optical-based interconnection network research and computational models. Conclusions are given in Section 4.

2 A Holistic Viewpoint

In this section we establish a classification based on the nature and roles of the interactions between each of three important domains that influence optical/optoelectronic interconnection network research, namely, electrical-based interconnection network research, optical-based interconnection network research and computational models. Specifically, we focus on characterizing the relationships between (a) electrical-based interconnection network research and optical-based interconnection network research and (b) optical-based interconnection network research and computational models.

Three broad areas which influence the development and deployment of optical/optoelectronic interconnection networks have been identified. These areas are:

1. **Electrical Interconnection Networks**: Electrical-based interconnection networks have almost ubiquitous use in computing systems. In our investigations, we have characterized these types of interconnection networks by considering such factors as their topology, performance metrics, message routing, fault tolerance, and abstract general framework of representation provided by graph embedding and product networks. We have further considered a rough ordering based on the degree of influence that these factors have on interconnection networks. Thus, topology and performance metrics have the most influential role, routing and fault tolerance have less influence and finally, graph embedding and product networks have the least influence. This characterization is illustrated in Figure 1 by the largest circle placed closest to the center, and successively smaller and more remotely located circles representing those factors of lesser influence.

2. **Optical and Optoelectronic Interconnection Networks**: We have also considered characteristics of optical and optoelectronic interconnection networks. The optical domain itself is characterized by the use of light as the information carrier. Two related fields of study include optical computing and optical telecommunications, the former using optics as the basis for logical gating and the latter using optics for information transport purposes. This characterization is also illustrated in Figure 1. Further details of the characteristics of optical and optoelectronic interconnection networks are presented in Section 3.1.

3. **Computation**: We have further considered the impact of optical/optoelectronic interconnection networks on the computation. Classical studies in parallel and distributed algorithms and processing have shown that different (parallel) algorithms must be considered for different electrical-based interconnection network topologies [9]. Indeed, computations often need to be 'tailored' to the particular interconnection network parameters.

   Traditional advances in parallel and distributed processing reflect in several programming issues: specification (requirements) of multiple process programs, programming language construction and associated compiling environments, and scheduling and load balancing. These sub-areas affect, for the most part, the degree of burden of multiple process execution and management placed on the programmer or on the compiling system.

Deployment of optical-based networks introduces the near certain expectation of impact upon computations. Further details of the nature of this impact are given in Section 3.2.

The triangle intersection shown in Figure 1 illustrates the integration of the knowledge and issues from the electrical, computational and optical domains.

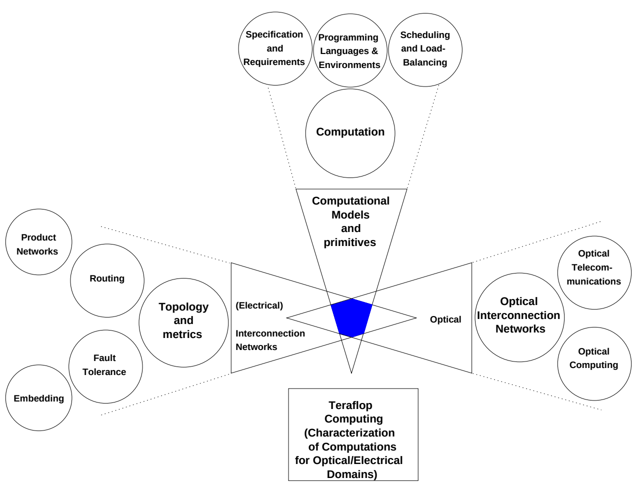

Figure 1: A holistic viewpoint of research inherent in optical-based interconnection networks.

A further relational abstraction of the interactions between the three domains is illustrated in Figure 2. Three types of relations can be defined, exactly, one relation between each of the domains. In particular, the association between the electrical and computational domains is represented by the relation `R(Electrical, Computational)` and that between the optical and computational domains by the relation `R(Optical, Computational)`. Characterizing these two types of relations leads is expected to provide heightened understanding of how computations may be best executed. The relation type represented by `R(Electrical, Optical)` expresses the development of optical-based interconnections networks as derived from the electrical-based counterparts. Lastly, a 'point' in the shaded intersection of Figure 1 is shown as the black dot in Figure 2. The black dot represents the relationship `R(Electrical, Optical, Computational)` and provides for the context of a holistic study of optical/opto-electronic interconnection networks.

In the subsequent section, we explore further the nature of the relationships `R(Electrical, Optical)` and `R(Optical, Computational)`. In particular, more specific relations are considered in these two relational categories.

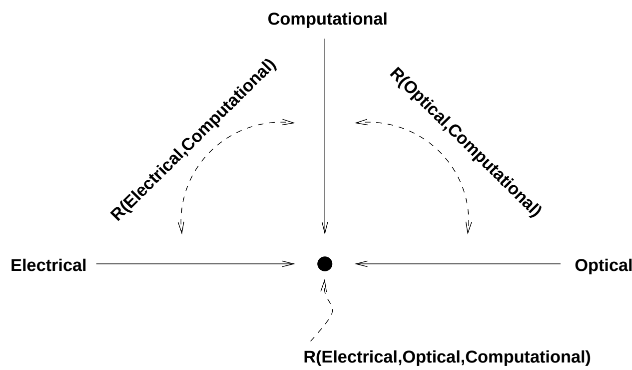

Figure 2: A relational abstraction of the research work involved in optical-based interconnection networks.

3 Relationships

3.1 Optical-Electrical

This discussion focuses on those aspects of electrical-based interconnection network issues which have been significantly influenced the development of optical/optoelectronic interconnection networks. We have identified that all-but-one of the sub-areas of electrical-based interconnection network research have been used in the development of optical-based interconnection networks. Figure 3 illustrates those sub-areas of Optical-based interconnection networks which have been developed based upon consideration of their counterparts in the electrical domain.

The primary influence on the development of optical/optoelectronic interconnection networks has come from topology and metrics. Some of the electrical-based topologies that have contributed to optical-based interconnection networks are: the fat tree [4], mesh/crossbar [10], omega network [1], hypercube [5], and mesh and hypercube hybrid [6].

Performance metrics from the electrical domain have also been frequently used to characterize the 'goodness' of optical/optoelectronic interconnection networks. The network diameter has frequently been used for comparison purposes [4].

To a lesser extent, routing in optocal/optoelectronic networks have been influenced from their electrical domain counterparts [4].

The product networks and graph embedding subareas have the least influence on the development of optical-based interconnection networks. Product networks have been considered in [5] while graph embeddings have been considered in [11, 12].

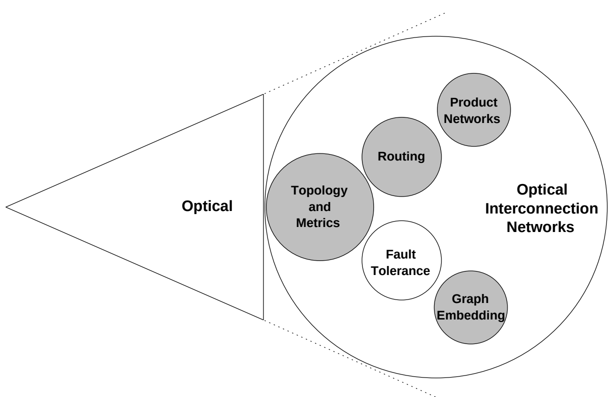

Figure 3: Components of optical-based interconnection networks that have been derived from the electrical domain counterparts.

In Section 2, the relative importance of the subareas, topology and metrics, routing, fault tolerance, product networks and graph embedding was presented in the context of the influence these subareas had on electrical-based interconnection networks. A similar case can be made regarding these subareas in the optical domain, where the relative importance is in the context of the strength of the influence from the electrical domain to the optical domain. Figure 3 illustrates this relative importance by the constituent circles having smaller diameter and placed more remotely away from the triangle.

Although fault tolerance is included into the optical domain in our study, we have observed that there is little degree of influence from the electrical domain for this subarea. We suggest that the state-of-the-art of optical/optoelectronic interconnection network research is such that viable deployment of optical-based technology, together with appropriate model abstractions, represents the primary and current focus of this field. This observation is consistent when also considering the development of a new field of study.

Based upon the strength of the relationship `R(Electrical,Optical)`, we characterize this relationship as one of *technology transfer*.

3.2 Optical-Computational Relationships

This section explores the effects that the unique features of the optical interconnection networks have upon the computation. There are two important questions to be addressed:

1. What impact is due to the high bandwidth and speed of optical networks?

2. What impact is due to the the incorporation of computation into the optical domain.

Figure 4 illustrates the possible areas of impact that optical interconnections networks may have upon computation. Two types of optical and optoelectronic models can be identified: *architectural models* are based on physical implementations whereas *virtual models* provide for higher levels of abstraction. More specifically, the former consists of the Architecture Layer and the Access Layer whereas the latter consists of the Access Layer and the Functional Layer. One example of an architectural type model is LIGHTNING [4] while an example of a virtual model is LARPBS [7].

In the case of LARPBS, the possibility exists that this virtual model is directly implementable. We show this possibility in Figure 4 by the dashed box at the Architecture Layer in the virtual model category. The significant difference between the two types of models is reflected in the Functional Abstraction Layer, that is, the virtual model type provides for a set of computation and communication primitives which can be used as building blocks in the construction of a computation.

Our investigations suggest that the impact due to bandwidth and speed of the optical networks is best answered by consideration of the architectural models whereas, the impact due to the incorporation of computation into the optical domain is best answered by consideration of the nature of the primitive abstractions provided by the virtual network models.

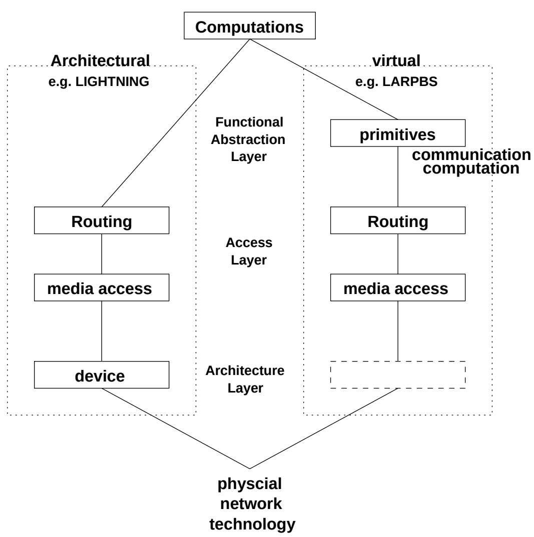

Figure 4:

4 Conclusions

We have provided a classification of the state-of-the-art issues in optical and optoelectronic interconnection research. This classification is in the context of a holistic view of the field. As part of this view, we have considered the global framework inherent in the research of this field, specifically, the identification of electrical-based, optical-based and computational domains; and the nature of the relationships between these domains, in the context of optical-based interconnection network research and development.

We have also identified some of the significant relationships that exist in this context. Two types of relationships have been considered: electrical-to-optical and computational-to-optical. We have shown that the electrical-to-optical relationships are characterized by a technology transfer from one domain to the other. We have also presented two specific observations regarding the computational-to-optical relationships, that is, the speed of the network and the possible combination of computations into communication.

In the two cases, (a) the technology transfer from the electrical to the optical domain exhibited in the current literature and (b) the deployment of optical-based technology for communication speed increases can be described as *evolutionary*. However, the impact that optical-based interconnection networks have on computations can be described as *revolutionary*. In [13], the authors point out that the economics of commercialization tend to favor evolutionary technological growth. The investigations of this paper support the claim that the start-of-the-art exhibits evolutionary growth.

A more exciting scenario for growth is based on the potential impact that optical interconnection networks have upon the nature of the computations. Our investigations suggest that some contributions have been made in this area.

References

[1] T. H. Szymanski, "Parallel computing with "intelligent optical networks"," in *Parallel Computing Using Optical Interconnections* (K. Li, Y. Pan, and S.-Q. Zheng, eds.), pp. 25–46, Kluwer Academic Publishers, 1998.

[2] T. H. Szymanski, A. Au, M. Lafrenière-Roula, V. Tyan, B. Supmonchai, J. Wong, B. Zerrouk, and S. T. Obenaus, "Terabit

optical local area networks for multiprocessing systems," *Applied Optics*, vol. 37, pp. 264–275, January 1998.

[3] K. Li, Y. Pan, and S.-Q. Zheng, "Preface," in *Parallel Computing Using Optical Interconnections* (K. Li, Y. Pan, and S.-Q. Zheng, eds.), Kluwer Academic Publishers, 1998.

[4] D. C. Hoffmeister, J. Chu, J. A. Perreault, and P. Dowd, "LIGHTNING network and systems architecture," in *Parallel Computing Using Optical Interconnections* (K. Li, Y. Pan, and S.-Q. Zheng, eds.), pp. 3–23, Kluwer Academic Publishers, 1998.

[5] A. Louri and B. Weech, "Scalable optical interconnection networks for large-scale parallel computers," in *Parallel Computing Using Optical Interconnections* (K. Li, Y. Pan, and S.-Q. Zheng, eds.), pp. 47–76, Kluwer Academic Publishers, 1998.

[6] C. fang Wang and S. Sahni, "OTIS optoelectronic computers," in *Parallel Computing Using Optical Interconnections* (K. Li, Y. Pan, and S.-Q. Zheng, eds.), pp. 99–116, Kluwer Academic Publishers, 1998.

[7] Y. Pan, "Basic data movement operations on the LARPBS model," in *Parallel Computing Using Optical Interconnections* (K. Li, Y. Pan, and S.-Q. Zheng, eds.), pp. 227–247, Kluwer Academic Publishers, 1998.

[8] S. Rajasekaran and S. Sahni, "Fundamental algorithms for the array with reconfigurable optical busses," in *Parallel Computing Using Optical Interconnections* (K. Li, Y. Pan, and S.-Q. Zheng, eds.), pp. 185–204, Kluwer Academic Publishers, 1998.

[9] V. Kumar, A. Grama, A. Gupta, and G. Karypis, *Introduction to Parallel Computing, Design and Analysis of Algorithms.* Redwood City, CA: The Benjamin/Cummings Publishing Company, Inc., 1994.

[10] T. H. Szymanski, "Hypermeshes: Optical interconnection networks for parallel computing," *Jounal of Parallel and Distributed Computing*, vol. 26, pp. 1–23, 1995.

[11] Y. Mei and Chunming-Qiao, "Embedding binary trees in arrays with optical busses," in *Proceedings of the Fourth International Conference on Massively Parallel Processing Using Optical Interconnections* (J. Goodman, S. Hinton, T. Pinkston, and E. Schenfeld, eds.), (Montreal, Canada), June 1997.

[12] T. H. Szymanski and H. S. Hinton, "Reconfigurable intelligent optical backplane for parallel computing and communications," *Applied Optics*, vol. 35, pp. 1253–1268, March 1996.

[13] C. B. Stunkel, "Commercial MPP networks: Time for optics?," in *Proceedings of the Fourth International Conference on Massively Parallel Processing Using Optical Interconnections* (J. Goodman, S. Hinton, T. Pinkston, and E. Schenfeld, eds.), (Montreal, Canada), June 1997.