A Free Space Optical Bus Parallel Model Framework

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***Abstract*—** *Optical bus parallel computing models have gained research interest in recent years. Two types of models have emerged, the fiber-based models are theoretically relatively mature and used for algorithm design whereas free space models are more architecture-oriented but less theoretically mature. This paper proposes a framework model for describing attributes necessary for a viable free space bus architecture. Subsequently, the framework guides the design of a basic free space optical bus architecture that is based on a particular fiber-based model. In this way, the maturity of fiber-based models is combined with the advantages provided by free space optics.*

Keywords: Optical bus, Parallel computing, Free space optics.

I. Introduction

Today's teraflop supercomputing brings substantive computational power to scientific and data intensive applications. A key component is the interprocessor interconnection network that supports the communications induced by the applications. High speed and high bandwidth interconnects are important in supporting the data communication requirements of modern day supercomputing applications. Interest in optical based interconnection networks is fueled by expectations that these kinds of networks could better support communication needs in these applications.

Optical bus parallel computing models are a recently proposed type of parallel model which uses an optical bus interconnection network to provide the communication medium in a multiple processor system. The high bandwidth and high speed communications of the bus interconnect together with the unidirectional propagation of communication messages combined with a unique processor addressing and message routing scheme lead to many interesting algorithms.

There are two major types of optical bus models described in the literature. Most models are fiber-based theoretical models for which many algorithms have been developed. Only limited work appears on free space optical buses. Advantages of free space optical bus parallel computing models over the fiber-based versions include increased data speeds, increased bus utilization and efficiency, and, possible increased data rates.

This paper first proposes an architecture framework for free space implementations of a corresponding particular fiber-based model and second, details one such free space optical bus architecture. The paper is organized as follows. Background information including a brief presentation of the fiber-based LARPBS optical bus parallel model is given in Section II. The proposed framework for free space optical buses in presented in Section III. Applications of the framework model to an existing architecture in the literature is given in Section IV. In Section V, we propose a particular architecture, within our framework, and which is based on fiber-based models. Conclusions are given in Section VI.

II. Background

Engineering and systems development work beginning in 1987 and continuing into the early 1990's established the feasibility of fiber-based optical bus models [1]–[3]. The first of many such models was proposed in 1990, the Array of Processors with Pipelined Buses (APPB) and its variant using switches (APPBS) [4]. Nowadays, the two most popular models are the Array with Reconfigurable Optical Buses (AROB) [5] in 1995 and the Linear Array with a Reconfigurable Pipeline Bus System (LARPBS) [6] in 1996. The latter has proven to be more popular in the literature [7]. Several of the proposed models touch on systems and implementation issues, however, the majority of the research has concentrated on algorithm development [7]. Recently, the Restricted LARPBS model (RLARPBS) [8] and the Parameterized LARPBS (LARPBS(p)) [9] focus on systems issues. In [10], [11] an optical power budget model for the LARPBS based on newly available optical technologies is described.

The LARPBS model is shown in Figure 1. Processors arranged in a linear array labeled P_0 to P_{N-1} are placed in the interior. The optical bus is comprised of three distinct waveguides (fiber) which are placed around the processor array. Optical pulses are introduced via injectors onto the waveguides along the upper (transmitting) segment. Due to the unidirectional propagation of light, these optical pulses travel along the transmitting segment (in the figure, from left-to-right), around the fold and along the lower (receiving) segment (right-to-left). Detectors are placed along the receiving segment. Messages are communicated along the message waveguide. Addressing and message routing are provided by the coincident pulse technique.

The coincident pulse technique requires the two waveguides labeled select and reference. Fixed delays of duration ω are placed on the receiving segments of the reference and message waveguides (shown as the dark-gray circles in Figure 1). Addressing works as follows: first, the source processor sends a reference pulse at the same time of the message. Then, depending on the destination processor's address, the processor waits integral units of ω to send a select pulse. There is a relative time delay between the two signals. The fixed delays on the receiving segment will adjust this time delay. Each successive delay will shorten the relative time delay between the two signals. When the signals coincide, the detector detects the 'double height pulse' and in turn, causes the processor to read the data on the message waveguide. So, to address P_{N-1}, the reference and select pulses have no relative time dilation between them: the two pulses are injected at the same time on the transmitting segment, travel together around the fold, and coincide at the detector of the first processor after the fold. To address P_{N-3}, a two ω time dilation is required. In addition, conditional delays, labeled S_i, are placed on the transmitting segment, one in-between each consecutive injector. These switches provide a program controlled mechanism to change the relative time delays of the messages during message transmission.

The model also incorporates bus partition switches, labeled as B_i in Figure 1. These switches allow for a program controlled mechanism to split the bus into multiple and independent sub-buses.

Free space optical signals propagate faster than that for fiber-based communications: 299792458 m/s in vacuum and approximately 299702547.2 m/s in air [12] compared with approximately one third slower in fiber [12], [13]. In addition, the denser space multiplexing capability of free space systems allow for greater numbers of communication channels per volume. Moreover, many free space optical commercial systems report data rates of 1.25, 2.5 Gbps with some reporting as high as 10 Gbps. It is also reported that demonstration systems can achieve rates up to 150 Gbps [14]. The commercial data rates are comparable to fiber-based systems; future free space data rates may exceed these rates.

There are many publications in the literature that describe free space optical buses. In [15], a single communication is split into multiple point-to-point light paths that are space multiplexed to provide all necessary processor-to-all communications. An optical bus using cascaded arrays of Selfoc lenses which is suitable for free space deployment is described in [16] and a free space optical bus using cascaded vertical-too-surface-transmission electrophotonic devices is described in [17]. A 2-D configuration of parallel free space optical buses is described in [18]; this model more closely resembles the fiber-based counter-parts than the other free space models surveyed here. Other models are described in [19]–[22]. The latter describes an optical backplane bus variation. There is much additional work reported in this area, especially, in conjunction with holographic components. However, all of these models appear to have been developed

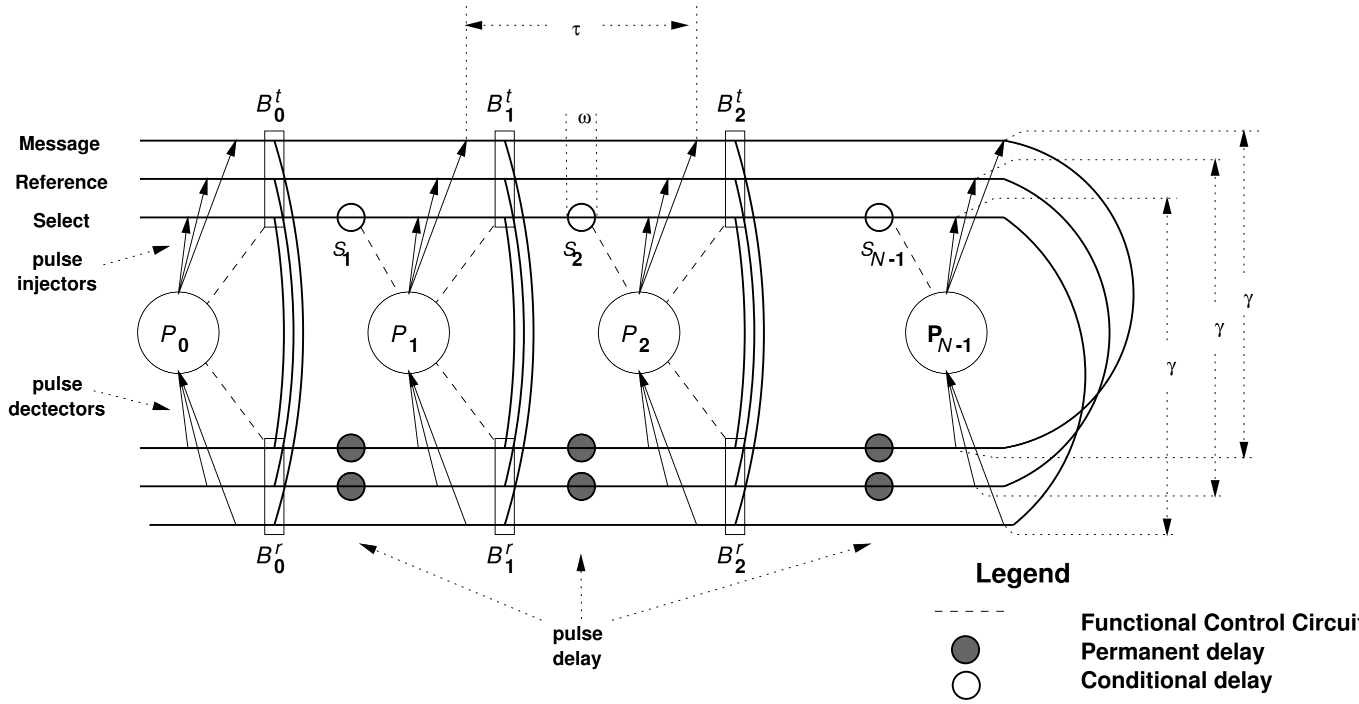

Fig. 1. The LARPBS model

independently of the fiber-based optical bus parallel computing models.

The advantages of free space optical bus parallel computing models over the fiber-based versions include increased data speeds, increased bus utilization and efficiency, and, possible increased data rates. Moreover, the maturity of fiber-based optical bus models can be combined with these advantages resulting in more beneficial optical bus parallel model implementations.

III. Free Space Optical Bus Framework

Optical buses must support communication related functions. The Framework Model breaks down these functions and describes them in terms of three levels. The three levels are the Physical Level, the Bus Space Level, and the Interconnection Level. The levels, respectively, deal with components, the environment in which the components reside, and the functions that the components provide.

The Framework Model provides criteria useful to analyze an architecture as a potential free space optical bus candidate. It is sufficiently flexible to allow choices for the physical components. Once selected, the model guides the specific descriptions of the bus space and interconnections between bus space and physical components thereby leading to a full systems specification of a particular architecture. In so doing, the architecture is defined to be a free space optical bus model.

A. Physical Level

The Physical Level describes the actual components and their layout. Components provide fundamental communication utilities which include such functions as allowing processors the ability to introduce communications onto the bus (injectors) and retrieve communications from the bus (detectors). Also, components exist to guide messages through the bus. The physical layout of these components is extremely important. The use of certain components may necessitate a particular physical layout due to constraints of the components themselves. The choice of certain component will reflect in the efficiency of the bus.

B. Bus Space Level

The second level is the Bus Space itself. The Bus Space describes the spatial environment of the message paths, namely: the bus space is the implied bounded volume in which the communications occur. The Bus Space Level is built upon the Physical Level. It is the combination of the free space environment and physical components. From the Physical Level, components are necessary to direct messages through the Bus Space and onto a particular destination. The volume expands as large as necessary in order to allow line-of-sight between various components as well as allowing for the redirecting of the signal path.

C. Interconnection Level

The Interconnection Level is the third level. This level is built upon the Bus Space Level in such a way that it describes the interface between the Physical Level and the Bus Space Level. The Interconnection Level describes the ordered functions that take place during a communication: a data signal is initiated by a processor, leaves that physical component via the injector component, travels through the Bus Space, and is reintegrated into the physical components of detector and processor upon receipt. Due to the optoelectronic nature of the overall system, electrical-optical conversions as well as bounded-free space conversions occur at the interfaces of the Physical and Bus Space Levels. The interactions and translations that occur at each step are described at this level.

IV. Application to Existing Architectures

The Framework Model is applied to the free space optical bus architecture proposed in [15] to illustrate the uniformity of our approach. The various parts of the architecture are identified into the three corresponding levels of the Framework Model.

A. Physical Level

The Physical Level consists of, specifically: laser diodes, lenses, Dammann gratings, polarization beam splitters, quarter wave plates, mirrors, SEED (Self Electro-optic Effect Device) devices, CMOS Photodetectors, pass-through devices and processors. Further details are provided in [15].

B. Bus Space

Many of these devices are organized into a communications 'plane'. The plane is comprised of a horizontal row of SEED modulators (the injector), a diagonal row of photodetectors (the detector) and a set of pass-through devices. Each plane is vertically offset from the previous by a single row. Mirrors are used to redirect the light from the last plane to the first plane if necessary. This bus space uses space multiplexing as an addressing scheme, that is, messages are separated by areas on the plane. The plane's physical layout, specifically, the configuration of the light paths with respect to the plane's area provides for message transmission, detection and pass-through.

C. Interconnection

Each processor is connected to a plane. At each interconnection location, a laser diode is used in conjunction with a Dammann grating to generate an array of beams. These beams are directed onto a SEED device which in turn injects the signal into the Bus Space. Each SEED device provides an outgoing link to another plane in the system. Each photodetector provides an incoming link to a processor from another plane. Together, these devices provide links to all of the planes in the system, hence, to all of the processors.

V. A Basic Free Space Optical Bus Architecture

This architecture is a straightforward basic model that is based on the architecture of the fiber based optical bus with a one-dimensional processor design, specifically, the LARPBS model. The Basic model will perform the same functions as the fiber based bus. In particular, it consists of all the necessary components for the successful generation, transmission and reception of messages. As before, the various parts of this architecture are identified into the three corresponding levels of the Framework Model.

A. Physical Layer

The physical components for the design include the following:

- Processors: There are n processors arranged in a linear row labeled 0 through $n-1$. Processors can send and receive data as well as perform computations.
- Injectors: There is one injector per processor. Each injector consists of three laser diodes

aligned in a horizontal pattern, one each for the select, reference and message functions.
- Detectors: There is one detector per processor. The configuration of detectors matches that of the injectors, that is, one device each for the select, reference and message functions. Each device consists of a fiber photodetector codrawn from conducting, semiconducting and insulating materials [23].
- Mirrors: Mirrors are used to guide messages through the Bus Space.
- Fixed Delay Devices: A specially configured device consisting of mirrors is used to delay the light signal to support the coincident pulse addressing scheme.

B. Bus Space Layer

The bus space is bounded by the volume necessary for the injection devices, the traversal path, the redirection devices and the detection devices of the N light beams. The volume needed for the bus space is dependent on the number of processors. It is possible to align the devices such that the light beams will not cross. Once the signal is in the bus space, it is assumed possible to use a combination of timing and distance adjustments to allow the signals on the bus to remain equidistant apart. The speed of the signal is dependent on the free space medium, assumed to be air in this paper.

The light beams are redirected in the bus space by specially designed mirrors. The mirrors are curved in such a way to allow all the N possible beams to be directed along a single path in the receiving segment. This configuration applies independently to each of the select, reference and message paths. The single light path along the receiving segment (for each of the select, reference and message paths) represents a pipelined multiplexed system, similar to that of the LARPBS model. The receiving segment also includes the fixed delay devices, again, similar to that of the LARPBS model.

C. Interconnection Layer

Signals are introduced onto the bus via injectors. The injectors are driven by the electrical signals output from processors. Hence, this defines an electro-optic bridge between the Physical and the Bus Space levels. The injectors have a specific layout requirement such that the generated signal from each injector is focused onto a particular location on the transmitting segment mirror.

Signals are detected by the fiber photodetector devices [23]. This is relatively new technology, although, many other photovoltic-based detectors have been proposed elsewhere. The fiber photodetector consists of a fiber which, when illuminated by a photon stream, generates an electrical signal. The detector proposed here uses spatially offset fibers, one per processor, to allow detection based on a portion of the signal while allowing the greater portion of the signal to pass by. These detectors define an opto-electrical bridge between the two levels.

D. Construction of the bus

A full description of the basic free space bus architecture is given by tying together the three levels of the Framework Model above. Figure 2 illustrates the completed model. Processors are arranged linearly labeled P_0 through P_{N-1} with the P_{N-1} processor aligned closest to the 'fold' formed by the two mirrors (right-hand side of the figure). The injectors are positioned such that the constraints of equidistance and same relative propagation are maintained. On the receiving segment, both the detectors and the delay devices are positioned to be calibrated with the signal path. The fiber detection devices are shown offset in the figure by the vertical dashed line. The delay devices generate an integral ω delay between each processor. These delays are placed on the reference and message light paths. Lastly, the dashed arrows to/from the processors illustrate the electrical-optical bridge.

The operation of the basic free space bus architecture is functionally the same as that of the LARPBS model. In this way, all of the algorithms designed for the LARPBS model are directly applicable for our model.

VI. Conclusions

A number of optical bus models have been proposed in the literature. Two types of models have emerged, the fiber-based models are theoretically relatively mature and used for algorithm design whereas free space models are more architecture-oriented but less theoretically mature. This paper

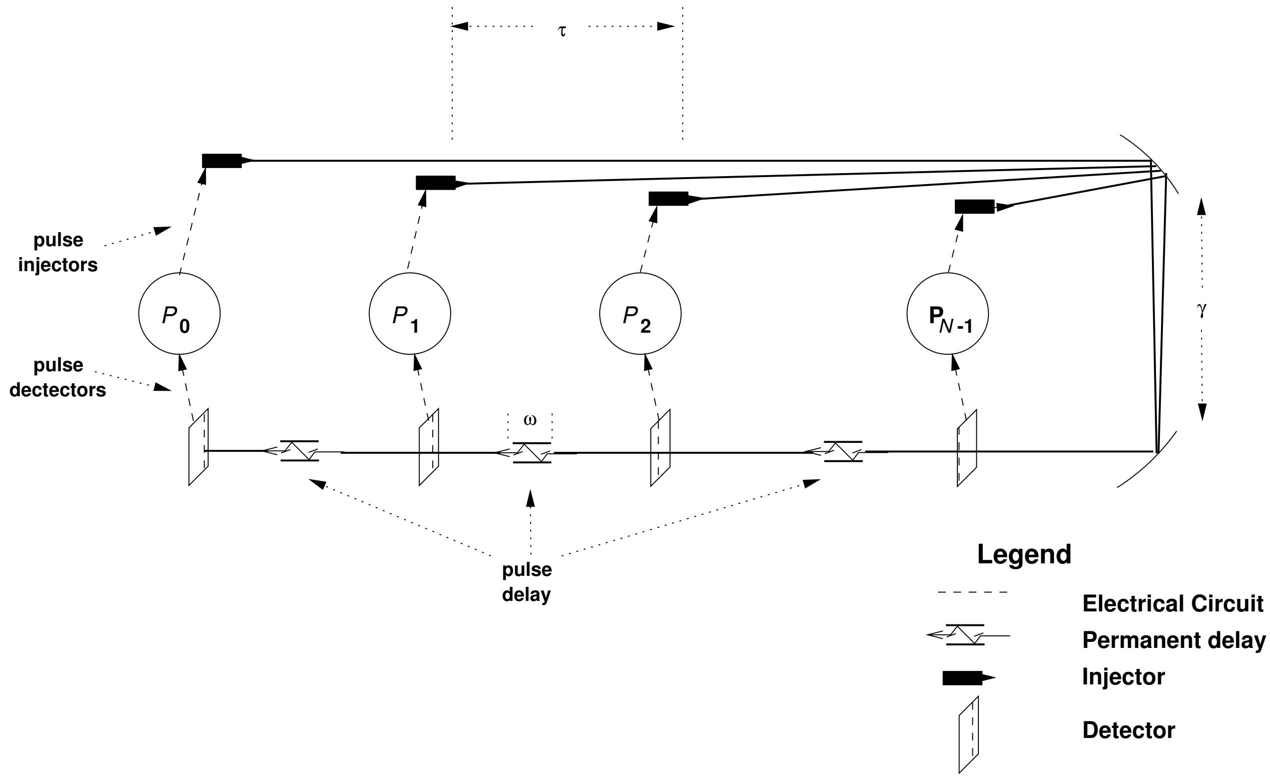

Fig. 2. The basic free space optical bus architecture

proposes a framework model and demonstrates the use by describing both a legacy model and a new architecture. The framework guides the design of new architecture that is based on the LARPBS model. In this way, the maturity of fiber-based models is combined with the advantages provided by free space optics. These advantages bring to existing algorithms increased bandwidth, speed and possibly, communication efficiency.

The approach taken in this paper follows the philosophy of some recent papers, notably, that of the LARPBS(p) model [9] where the LARPBS model is considered independent from its implementation. The LARPBS(p) parameters in fact, were developed based on the idea that different implementable architectures could be devised for LARPBS; the architecture proposed in this paper fits within this context. Furthermore, the Framework Model does not preclude development of other types of architecture designs. Our present work considers some alternative designs guided by the Framework Model.

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