A Preliminary Feasibility Study of the LARPBS Optical Bus Parallel Model

René Roldán [a], Brian J. d'Auriol[a]

[a]Department of Computer Science, The University of Texas at El Paso, El Paso, Texas, 79968, USA
roldan@cs.utep.edu, dauriol@acm.org

Current and future parallel processing systems require high bandwidth interconnects to satisfy the communication demands. Optical technologies have been proposed to address the bandwidth limitation of electrical bus systems. Specifically, during the past decade, several optical bus parallel models have been proposed, together with a suite of basic and advanced algorithms. One of the more popular optical bus models is the Linear Array with Reconfigurable Pipelined Bus System (LARPBS), appearing in 1996. Since then, many publications present mostly theoretical work concerning LARPBS algorithms, and only limited comments regarding the implementation of this model have been noted. This paper assesses the realistic and practical nature of the LARPBS optical bus parallel model with respect to recent available optical technologies. An optical power and signal loss analysis for the LARPBS model is conducted. A straight forward implementation of the bus model without amplification of optical signals suggests high losses that limit the number of processors to between eight and twelve. Nevertheless, this work also suggests that variations in the architecture may lead to more practical parallel systems.

Les systèmes de traitement parallèle, présents et futurs, nécessitent une interconnectivité à haut débit qui satifasse aux besoins de communication. Des technologies basées sur l'optique ont déjà été proposées pour palier à la limitation de débit des systèmes électroniques à architecture bus. Plus précisément, plusieurs systèmes parallèles à bus optique ont été mis de l'avant au cours de la dernière décade, lesquels sont accompagnés par des algorithmes de traitement plus ou moins avancés. Un des systèmes optiques les plus connus est le "Linear Array with Reconfigurable Pipelined Bus System" (LARPBS) qui a fait son apparition en 1996. Depuis lors, plusieurs articles théoriques ont portés sur les algorithmes LARPBS, mais on y trouve peu d'informations sur l'implémentation de tels systèmes. Le présent document évalue le réalisme et les aspects pratiques dy système parallèle LARPBS à bus optique en regard des technologies optiques récentes. On y effectue une étude de la perte de puissance et de signal optique pour le système LARPBS. Une implémentation simple du système bus, sans amplifiation du signal optique, montre de fortes pertes qui limitent le nombre de processeur à un nombre variant entre huit et douze. Néanmoins, notre étude donne à penser qu'une modification de l'architecture pourrait conduire à la mise au point de systèmes parallèles plus réalistes.

1 Introduction

Current parallel processing systems require interconnections that can provide high bandwidth so as to satisfy the communication demands of a parallel system. One of the main motivations for the development and implementation of optical interconnects is to overcome the bottlenecks that electrical data buses produce due to their now relatively low bandwidth. High processing speeds of current technology have over-passed the physical limitations of electrical interconnections; in other words, in an electrical system, more data can be produced by computations than the data that can be transferred through its electrical data bus [1]. This paper focuses on optical bus technologies to overcome these limitations.

The bandwidth limitations in electrical interconnections stem from physical characteristics of the electrical conductors where the higher the frequency of the signal, the higher the loss of information. The quality of an electrical signal is frequency-dependent [1]. This characteristic does not apply to optical signals in optical fibers; there is not significant frequency-dependence loss [1]. The consequence of this is higher bandwidth for optical interconnects.

Optical interconnects can be based on one (or both) of the following two methods: a) free space interconnects and b) waveguided interconnects. The former utilizes free space (e.g. air) as the communication medium, thus the optical signals are not constrained to a waveguide. The latter utilizes waveguides (e.g. fiber) to constrain the path of the optical signal. Waveguided signals are somewhat slower than signals in free space due to the refractive index of optical fiber's material [1]. Although optical communication via either of these methods is possible, the clear majority of optical buses proposed in the literature utilize fiber for optical communication.

The Linear Array with Reconfigurable Pipelined Bus System (LARPBS) was first published in 1996 [2]. This is one of ten distinct fiber-based optical bus models that appeared between 1990 and 1998 (refer to [3] for a review of these models). Of the ten models, LARPBS appears the most popular based upon not only the number of publications that strongly relate to this model but also the extent of algorithm design, model extension and derived models from LARPBS (refer to [3] for an extensive literature review). Based upon the literature review, there appear to be three primary periods of optical bus model development: the period 1990 to about 1995 that is characterized by initial optical bus model development together with simplification attempts of such models, the period of about 1995 to about 1996 with the advance of two competitive bus models, AROB [4] in 1995 and LARPBS [2] in 1996, and the period post 1996 characterized by continued developments mostly of refinements in nature.

Despite the variety and popularity of optical buses in general, and LARPBS in particular, only limited and indeed early publications deal with the practical implementations of such parallel models. Work described in [5] lays the groundwork for optical bus implementations while the highly influential work in 1991-1994 [6,7] describe specific implementational details related to early optical bus architectures. Beyond this, we have not observed much in the way of recent efforts to consider the practical implementations of the more recent optical bus models, specifically, the LARPBS model. We do note however, that there is active work that addresses general engineering issues of optical interconnection networks in general. Also, optical technologies have advanced significantly during the past decade.

We are motivated, in part, by the claim in [2]: "...we believe that the LARPBS model is implementable and practical using current optical technology." The majority of later work on LARPBS mostly concern algorithm design and model refinements. There is therefore a need to investigate the realistic and practical modern implementation of optical bus based parallel models, specifically, the LARPBS model. For the feasibility study conducted in this paper, signal loss estimates are performed for the LARPBS model to determine the maximum number of processors that could be interconnected without the need of signal amplification. These preliminary results suggest the practical implementation, nevertheless restricted to low numbers of processors for a passive system. The results also suggest that further study and investigation is needed.

The paper is organized as follows. Related work on practical implementations conducted in the early 1990s is briefly reviewed in Section 2. A review of optical bus parallel models in general and LARPBS in particular is given in Section 3. In the spirit of this conference, a brief review of basic optics is given in Section 4 to assist less technical readers. A brief survey of optical devices suitable for optical buses is presented in Section 5. The main contribution of this paper, an estimation of the total number of processors for a passive LARPBS system appears in Section 6. Conclusions are given in Section 7.

2 Related work on Practical Optical Bus Implementations

In [6,7], the authors present two important results pertaining to optical fiber bus interconnections for a multiple processor system. First, the coincident pulse technique used for processor addressing in message routing is presented. Second, a feasibility study including power budget and scalability of such a multiple processor system is discussed. The authors specifically apply their analysis to an optical bus architecture consisting of primarily a single waveguide and using optical technologies of that period of time. In our work, we are specifically concerned with a more sophisticated optical bus model, the LARPBS [2] that appeared later, in 1996 and which incorporates architectural differences with respect to the earlier work. Furthermore, in this paper, we are particularly interested in the applicability of recent optical technologies, for example, VCSELs (Vertical Cavity Surface Emitting Lasers) and the standardization of optical carrier signals with supported data rates 10 to 40 times faster than available at the time of the early work.

In [7], results are presented that indicate in the order of 16 detectors (processors) could be supported by the system for a power margin of 20% when using 90% couplers. Also, under the assumption that the perceptible power for the photo detector could be 0.1% of the input power, results are presented that indicate that the total number of processors would be 50. These results are consistent with those we publish in this paper. Furthermore, we concur with the early observations that fiber amplifiers can be employed to extend the practical bus implementation.

3 Optical Bus Parallel Models

Several models for fiber-based optical buses have been proposed in the last two decades. One of the principal motivations is that large numbers of processors can be interconnected in linear or two dimensional topologies where the interconnect requires low power consumption without needing amplification for the signals. Other motivations include significantly increased bandwidths as well as pipelined communication. The latter is due to the physical characteristics of light when traveling in an optical fiber, i.e. unidirectional propagation and constant propagation time per unit length [8].

3.1 Brief Survey of Optical Buses

This section outlines in brief some of the important historical development of optical busses as introduction to the selection of the LARPBS for this study. The reader is referred to [9] for an excellent overview; also further details appear in [10] and historical presentations appear in [3,11].

One of the earliest forms of optical buses is the unidirectional bus where messages travel on a message waveguide from low numbered processors to high numbered processors. Three improvements made to this model include: a) the addition of a second unidirectional bus to allow communication from high to low numbered processors, b) the incorporation of coincident pulse addressing [12] induced the addition of two new waveguides, the select and the reference, and c) the incorporation of light transmission delays on the message and reference waveguides. Figure 1 illustrates a unidirectional bus with the three waveguides, but not with the second unidirectional bus.

The select and reference waveguides are utilized for processor addressing by employing the coincident pulse technique [12]. In this technique, and assuming that all three waveguides' fiber segments are all of the same length, a signal initiated on the select waveguide some delta time after a signal initiated on the reference waveguide will, if the transmission is not interfered with, reach a destination processor with the same delta time differential between the signals.

Destination addressing occurs when the transmission of reference signal is slowed in predictable amounts so that both the select and reference signals coincide at a desti-

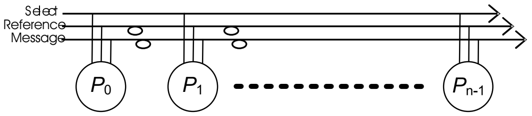


Figure 1. Unidirectional Bus with Reference, Select and Message Waveguides

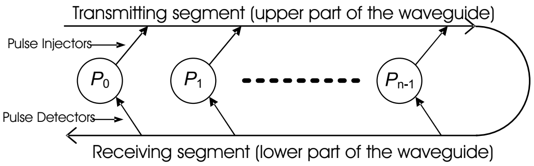


Figure 2. Folded One Dimensional Bus

nation processor (detection of the coincidence triggers the reading of the message waveguide). In Figure 1, unit delays are shown as small ovals on the message and reference waveguides. If each delay introduces an ω unit of delay, then Processor P_0 can address destination P_1 with an initial one ω time differential; P_1 can address P_3 with an initial two ω time differential, etc.

A common architecture is the folded one dimensional bus as shown in Figure 2. This configuration allows a single waveguide to communicate to all the processors in the system. Processors write messages to the upper side of the bus and read them from the lower side. Coincident pulse is often used for addressing, that is, three waveguides with delays on the reference and message waveguides *on the receiving segment only*.

A number of two and multi-dimensional optical bus architectures have also been proposed in the literature, for example, APPB/APPBS [13], RASOB [14], AROB [4] and PR-MESH [15]. In these cases, rows and columns of processors are interconnected either through processors or via optical switches. In general, these architectures conceptually extend a linear array topology. The results presented in this paper are applicable to such extensions.

3.2 The LARPBS Model

The Linear Array with a Reconfigurable Pipelined Bus System (LARPBS) [2] is a reconfigurable model of n processors identified as P_0 through P_{n-1}. LARPBS uses three folded waveguides, one for message passing and the other two for addressing. Addressing is accomplished via the coincident pulse technique. In addition to the fixed delays on the reference and message waveguides, LARPBS also includes conditional delays on the select waveguide in the transmitting segment only. This provides, in addition to the initial time differential between the select and reference signals, the option to adjust that time differential by factors of ω. For example, P_0 can address P_{n-2} by sending out a select and reference pulse at the same time, and setting exactly one of the configuration switches to delay. The reconfigurability in this model is provided by the pairs of partition switches located between each processor on both the upper and lower segments; these switches can partition the system into two subsystems with the same characteristics at any of these pairs of switches. As a consequence, the total number of subsystems can be equal to the total number of processors. Figure 3 illustrates the LARPBS model. Further details about the LARPBS model can be found in [2,8].

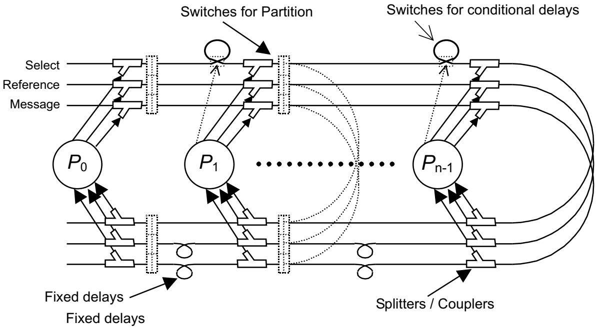


Figure 3. LARPBS -Linear Array with a Reconfigurable Pipelined Bus

In the theoretical model, an optical signal is initially generated by a pulse injector while the signal is detected by a pulse detector. Photo emitters are optical devices that implement the pulse injector function and the signal is routed into the fiber bus by an optical coupler. In a similar way, a photo detector and a splitter (coupler) implement the pulse detector function. The elements in this model which contribute a loss to the signal are the following:

- three waveguides: select, reference, and message,
- (n-1) partition switches,
- (n-1) conditional delay switches,
- (n) pulse injectors per waveguide (each injector is composed of a photo emitter and a coupler), and
- (n) pulse detectors per waveguide (each detector is composed of a photo detector and a coupler).

In this paper, we confine ourselves to the feasibility of the LARPBS model [2].

4 Review of Basic Optics and Measuring Units

4.1 Refractive Index and Total Reflection

Light travels at different speeds in different transparent media where the denser the medium, the slower the speed of light. When a beam of light in a transparent medium reaches a boundary with another transparent medium, two phenomena may occur: refraction and reflection. Refraction occurs when part of a light beam passes through the

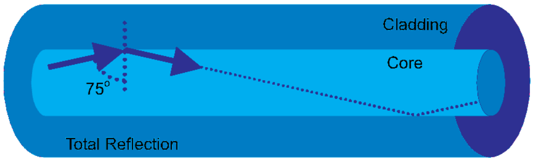


Figure 4. For Total Reflection to take place in a fiber, the minimum angle of incidence is about 75^o.

other medium and suffers a deviation if the incident angle is small enough but greater than zero. Reflection occurs when part of the light beam is reflected back into the original medium. If the incident angle is sufficiently large then the phenomenon of total reflection [16,17] occurs; this means that no portion of the beam escapes from the original medium due to refraction. The amount of deviation of a beam due to refraction between free space and another transparent medium is called the refractive index (RI) of the medium. The RI indicates how dense a medium is with respect to free space in terms of light transmissibility and also is an indication of how fast light travels in that medium [16]. The speed of light in a medium is obtained by dividing the speed of light in free space, c = 299,792,458 m/s, by the RI of the medium: $v = \frac{c}{n}$ [18]. For example, if the RI for optical fiber is n=1.47 then the speed of light in the optical fiber is 203,940,447 m/s, which is about 30% slower than that in free space. Light transmission in a fiber is mostly enabled by the total reflection of light within the core due to the difference of refractive indices between the core and the cladding, as shown in Figure 4.

4.2 Gain and Loss

Any transmission line causes attenuation to the signal it carries, some of this attenuation is caused by the conductor itself when other devices also contribute to the attenuation. Devices such as amplifiers provide for a gain to the power of the signal. Optical fiber introduces a very small loss to the signal, this loss is given in dB/Km (where dB refers to decibels) [19]. The unit dB was created by the Bell Telephone Company to facilitate the calculation of the total loss in a transmission line by replacing losses given in percents or factors by their corresponding logarithms [20]. By doing this, the total loss in a transmission line can be calculated by summing individual losses given in decibels. The unit decibel is defined as follows [19,20]:

$$\text{dB} = 10 \log \left(\frac{\text{Input Power}}{\text{Output Power}} \right)$$

4.3 Optical Power

Similarly to electrical power, optical power is measured in Watts (W). However in networks, powers are very small and are measured in the order of milliwatts (mW) [19] or in an equivalent but more practical unit called decibels relative to milliwatts (dBm) [19,20]:

$$\text{dBm} = 10 \log \left(\frac{\text{Power in mW}}{1 \text{ mW}} \right)$$

The input power value is considered as a factor of one which can be replaced by its logarithm. By doing this the total loss in the system can be subtracted from the input power in order to calculate the output power. For example, if the input power is 9 dBm and there are losses of 2 dB and 3 dB, then the total loss is 5 dB and is subtracted from the input power to give an output power of 4 dBm. Note that losses are given in dB and powers are given in dBm, nevertheless, they can be subtracted or added directly. Also note that negative powers given in dBm correspond to values which are less than 1 mW, e.g. 0.5 mW = -3.01 dBm [19] and that a loss of 3.01 dB corresponds to a power halving whereas a gain of 3.01 dB corresponds to a power doubling [19].

Table 1
VCSEL's Powers

VCSELs	
Wavelength	Emitting Power
850 nm	10dBm
1310nm	4dBm
1550nm	2dBm

5 Survey of Optical Devices

This section describes the optical technologies available currently, that is, post 2000, which can be deployed in realizing an LARPBS system. The inclusion of this section is necessary since for two reasons: first, we identify specific technologies and standard wavelengths as eligible for a realization for LARPBS, second, we lay the groundwork for the analysis conducted later in the paper.

5.1 Photo Emitters and Photo Detectors [17,21]

There are several kinds and technologies of photo emitters: LEDs (Light Emitting Diodes), Laser Photo Diodes, VCSELs (Vertical Cavity Surface-Emitting Laser). The latter is the most appropriate for LARPBS implementation due to its special features such as low cost, low power consumption, and easy coupling to optical fiber. VCSELs are now available in the three principal wave lengths: 850nm, 1310nm, and 1550nm. VCSELs provide different emission power for each of these wavelengths. Table 1 shows the respective powers for each wavelength [22,21].

There are also several kinds of photo detectors which do not vary technologically from one to another as much as photo emitters. Also, they are available in a wider range of options. For these reasons, the principal concern is the minimum power that they can detect. The minimum power perceptible by a photo detector is about 1μW, or -30dBm [21].

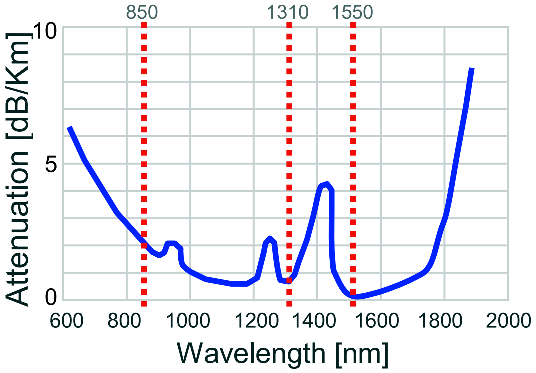


Figure 5. Fiber Loss (dB/km)

5.2 Optical Fiber

Optical fiber is the main component of an optical waveguided system; it is the communication medium through which the information is sent. The core is that part of the fiber which actually transmits the signal and whose refractive index is about 1.47. The cladding is made of a material with a smaller refractive index than the core to allow the effect of total reflection as shown in Section 4.1 and in Figure 4. Finally, the coating layer is intended for easy handling of the fiber since the size of the core and cladding are very small.

There are two main kinds of optical fiber: multimode and single-mode [16,17]. Multimode fiber is used to transmit several signals with different wavelengths at the same time while singlemode optical fiber is used to transmit monochromatic signals, that is, a single wavelength. Singlemode and multimode optical fibers differ on their core diameters, for example, singlemode has a core diameter of 10μm and a cladding diameter of 125μm whereas multimode has core diameters ranging from 50μm to 110μm.

Optical signals with different wavelengths suffer different losses in an optical fiber. Figure 5 shows a graph of signal attenuation for different wavelengths of light. Losses for the three principal wavelengths used in optical communication are given in Table 2. The minimum loss in a fiber corresponds to signals with a wavelength of 1550nm [23]. This is the ideal wavelength to use for telecommunication systems where distance and the length of the fiber are large. However for the expected scale of interconnection networks, loss due to the fiber may be negligible [1]. In particular, break even losses are calculated for lengths of approximately 5.7km or less. The vertical dotted lines, from left to right in the figure, show the chronological sequence of VCSELs as available commercially; only recently are the 1550nm emitters available.

From these three options the maximum loss in fiber occurs for a wavelength of 850nm as shown in Figure 5 and in Table 2. However since the loss of signal due to the length of the fiber is very small, a better consideration in choosing the appropriate wavelength is selecting the photo emitter that offers the maximum optical power. This extends as much as possible the interval between the emission power and the detection power. This is important so as to maximize the available power, thereby tolerating the greatest amount of transmission loss. Therefore, a wavelength of 850nm with an emitting power of 10dBm is selected.

Table 2
Loss in Optical Fiber

Loss in Optical Fiber	
Wavelength	Loss (dB/Km)
850nm	1.6
1310nm	0.65
1550nm	0.2

Table 3
Typical insertion losses in splitters [17]

Splitting Ratio	Typical Insertion Loss (dB)
50/50	3.1/3.1
40/60	4.1/2.3
15/85	8.4/0.8
10/90	10.2/0.6
5/95	13.2/0.4

5.3 Splitters and Couplers

Splitters or Couplers divide one optical path into two or more with any combination of splitting ratios.
Table 3 shows some common splitting ratios and their corresponding insertion losses.

6 Power Loss Analysis of LARPBS

This estimation of the number of processors in the LARPBS optical bus model considers the total loss of an end-to-end signal. Using the currently available devices for a wavelength of 850nm the total signal loss budget is about 40dB.

In order to carry out this analysis, it is necessary to identify where the losses occur and their respective amounts. Following from Section 3.2, the following presentation summarizes the optical components of interest with emphasis on the induced signal losses.

- Optical Fiber: Losses for 850nm wavelength are given in Figure 5 and Table 2. The loss depends on the fiber length. Either single or multimode fiber may be used, however, when using a single wavelength in LARPBS, there is no need to use multimode.

- Photo Emitters: VCSELs generating 850nm wavelengths are chosen to implement the emitters. The emitting powers are shown in Table 1. There is a

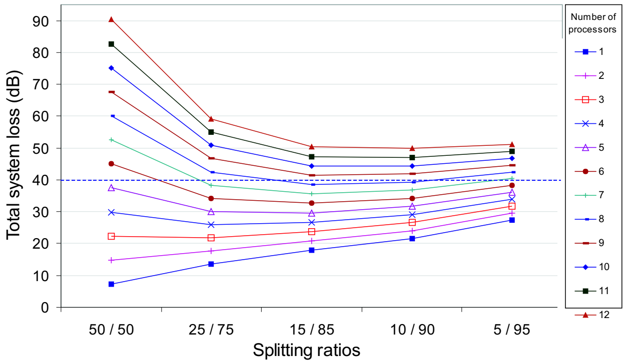


Figure 6. Number of processors vs. splitting ratios.

loss that corresponds to the coupling of the VCSEL to the fiber, this loss is between 0.4dB and 1dB [21].

- Photo Detectors: The minimum perceptible power for a photo detector is about -30dBm as discussed in Section 5.1. The coupling loss is between 0.4dB and 1dB.

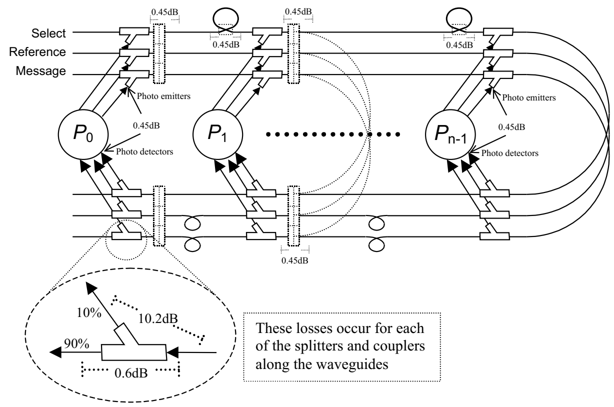
- Couplers and Splitters: Splitters introduce different loss depending on the splitting ratio as shown in Table 3. Figure 6 presents our analysis of the effects that different splitting ratios would have on the overall system (keeping the other parameters constant for this particular finding). Note that the power loss effect is minimal at splitting ratios 10/90 and 15/85. In the LARPBS system, this observation stems from balancing the losses along each of the out-bound paths, that is, we wish to reduce the costs along the longest path. We therefore select the 10/90 splitting ratio: 10% for the path that connects to the processor and 90% for the path that gives continuity to the waveguide. The corresponding losses for this splitting ratio are 10.2dB and 0.6dB respectively.

- Switches (for example as used for bus partitioning) either are the one-input, two-output or two-input, one-output variety. In the former, 100% of the signal is switched to the appropriate output whereas in the latter, an either-or but not both coupling occurs. Losses on the average of 0.45db occur per switch.

Table 4 summarizes the maximum range of signal loss that can be tolerated, that is, 40dB.

Figure 7 shows the LARPBS model with the expected sources of signal loss.

Table 5 summarizes the known constant sources of signal loss for one optical communication: that is, from any specific source processor to any specific destination processor The fixed constant signal loss is calculated as: 21.46dB (for an assumed 100m maximum length of an optical path).



These losses occur for each of the splitters and couplers along the waveguides

Figure 7. LARPBS signal loss.

Table 4

Range of Loss in the system

Emitting power:	10dBm
Detector power:	-30dBm
Range of loss:	**40dB**

Since the intent of this study is to determine the maximum number of processors, note that each processor is considered as an assembly composed of an injector, detector, one conditional delay switch and two partition switches. For each processor in the system then, an optical signal must pass through this assembly and is subject to signal loss. The maximum number of processors can hence be estimated by considering a bus cycle, that is, a communication from P_0 to itself.

From the range of loss, 40dB, minus the fixed loss, 21.46, the variable loss should be less or equal to 18.54. Table 7 shows some calculations on the number of processors which can give valid variable and/or total losses. The maximum number of processors is eight.

If the reconfigurability that partition switches offer is sacrificed by removing them, some loss is eliminated. In that case the variable loss corresponds to (n-1)°0.45 + (2n-2)°0.6. Table 8 shows the results when partition switches are removed. The maximum number of processors is twelve under these conditions. Recall from Section 3.2 that LARPBS is a defined architecture that includes the bus partition switches for the purposes of dynamic bus reconfigurations during operation. Our analysis here should be viewed as estimating the cost for this characteristic of LARPBS.

7 Conclusion

An optical power budget and signal losses of an LARPBS optical bus parallel computing model are considered in this study. Accordingly, it is determined that an optical signal originating at the beginning of the bus, pro-

Table 5
Fixed losses for any optical path

Fixed Losses	
Loss Localization	Amount
Emitter Insertion Loss:	1×0.45 dB
Detector Insertion Loss:	1×0.45 dB
Fiber Loss:	0.16 dB/100m
Splitters Loss 10/90:	2×10.2 dB
Total Fixed Loss:	**21.46 dB**

Table 6
Variable loss for a path with n processors

Variable Losses	
Loss Localization	Amount
Partition Switches:	$(2n-2) \times 0.45$dB
Switches for delays:	$(n-1) \times 0.45$dB
Splitters Loss 10/90:	$(2n-2) \times 0.6$ dB
Total	$(3n-3) \times 0.45 + (2n-2) \times 0.6$

cessor 0, is able to reach, with sufficient power, the last processor in the receiving segment, which is again processor 0. Despite the loss of signal in this passive system, the number of processors that can be accommodated is about eight when the LARPBS model is complete with all the optical devices that are required. If the reconfigurability of the model is sacrificed, then the total number of processors can be increased to twelve due to the loss reduction from the absence of partition switches.

These results are promising despite the low order of processors. In the literature, the expectations of having large, on the order of hundreds or thousands, of processors has motivated the further development of such optical parallel models, in particular, the LARPBS model. Our results clearly establish the reasonable and practical implementation of the LARPBS optical bus parallel computing model using current optical technologies. In particular, VCSELs are used in our analysis.

Since two and multidimensional variations of optical bus parallel models extend from the one dimensional case, the approach we have taken can be applied to these other models as well. Our approach can also be applied to models that incorporate multiple optical buses as well.

Despite the decade long advancements, our results are are consistent with work reported a decade ago. Differences between our work and that reported earlier include: (a) the earlier work conducted an analysis of an architecturally simplified optical bus system to the one we have considered, that is, the LARPBS model, and (b) the earlier work applied technologies at that time whereas we conclude our work with current optical technologies.

Table 7
Number of processors and the corresponding losses

Number of Processors	Variable Loss ≤ 18.54	Total Loss ≤ 40
n=7	15.30	36.76
n=8	17.85	39.31
n=9	20.40	41.86

Table 8
Number of processor and corresponding losses when partition switches are removed

Number of Processors	Total Loss ≤ 40
n=11	37.96
n=12	39.61
n=13	41.26

The analysis conducted did not consider amplification of optical signals, as perhaps can be done by erbium-doped fiber. Also, a study of data rates along with a BER analysis lies outside the scope of the present work. The analysis did provide the major source of signal loss: splitters. In our future work, we consider amplification and alternative detector technologies to address the limitations on the number of processors. We also intend to continue the work by considering data rates and a BER analysis.

References

1. D. A. B. Miller. Physical reasons for optical interconnection. *International Journal of Optoelectronics*, 11:155–168, May-June 1997.
2. Yi Pan and Keqin Li. Linear array with a reconfigurable pipelined bus system — concepts and applications. In H.R. Arabnia, editor, *Proc. of the International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'96), Vol. III*, pages 1431–1441, Sunnyvale, California, USA, August 1996.
3. Marie Beltran. A safe communication model for optical buses. Master's thesis, The University of Texas at El Paso, Department of Computer Science, 2003. in progress.
4. Sandy Pavel and Selim G. Akl. On the power of arrays with reconfigurable optical buses. *Technical Report No. 95-374, Queens University, Kingston, Ontario, CANADA*, February 1995.
5. Donald M. Chiarulli, Rami G. Melhem, and Steven P. Levitan. Using coincident optical pulses for parallel memory addressing. *IEEE Computer*, 20(12):48–58, Dec. 1987.
6. D.M. Chiarulli, R.M. Ditmore, S.P. Levitan, and R.G. Melhem. An all optical addressing circuit: experimental results and scalability analysis. *Journal of Lightwave Technology*, 9:1717, 1991.
7. D. Chiarulli, S. Levitan, R. Mehlen, M. Bidnurkar, R. Ditmore, G. Gravenstreter, Z. Guo, C. Qiao, M. Sakr, and J. Teza. Optoelectronic buses for high-performance computing. *Proceedings of the IEEE*, 92(11):1701–1709, Nov.

1994.

8. Brian J. d'Auriol. Communication in the LARPBS (optical bus) model: A case study. In A. Goscinski et al., editor, *Proc. of The Fourth International Conference on Algorithms And Architecture for Parallel Processing (ICA3PP2000)*, pages 581–590, Hong Kong, December 2000.
9. Sartaj Sahni. Models and algorithms for optical and opto-electronic parallel computers. *International Journal Foundations in Computer Science*, 12:249–264, June 2001.
10. René Roldán. A fesability study for fiber-based optical bus networks. Master's thesis, The University of Texas at El Paso, Department of Computer Science, 2003. in progress.
11. L. Susan Draper. A free space optical bus system (FSOBS). Master's thesis, The University of Texas at El Paso, Department of Computer Science, 2003. in progress.
12. S.Q. Zheng, Keqin Lin, Yi Pan, and M.C. Pinotti. Generalized coincident pulse technique and new addressing scheme for time-division multiplexing optical buses. *Journal of Parallel and Distributed Computing*, 61:1033–1051, August 2001.
13. Zicheng Guo, Rami G. Melhem, Richard W. Hall, Donald M. Chiarulli, and Steven P. Levitan. Array processors with pipelined optical busses. In J. Jaja, editor, *Proc. 3rd Symposium on Frontiers of Massively Parallel Computation (Cat. No.90CH2908-2)*, pages 333–342, College Park, MD, USA, October 1990.
14. Chunming Qiao. Efficient matrix operations in a reconfigurable array with spanning optical buses. In *Proceedings. Frontiers '95. The Fifth Symposium on the Frontiers of Massively Parallel Computation (Cat. No.95TH8024). IEEE Comput. Soc. Press. 1994*, pages 273–280, McLean, VA, USA, Feb 1995.
15. Jerry L. Trahan, Anu G. Bourgeois, and Ramachandran Vaidyanathan. Tighter and broader complexity results for reconfigurable models. *Parallel Processing Letters*, 8(3):271–282, 1998.
16. Stamatios V. Kartalopoulos. *Introduction to DWDM Technology, Data in a Rainbow*. IEEE Press, 2000.
17. Force Inc., 2003. http://www.fiber-optical.info.
18. Optical Sciences Center 1630 E.University Blvd, Tucson, Arizona 85721, 2002. http://www.optics.arizona.edu/.
19. Light Reading, Inc, 2003. http://www.lightreading.com/document.asp?doc_id=6730&site=lightreading.
20. Paul H. Bock, Jr., 1994. http://www.columbia.edu/~fuat/cuarc/dB.html.
21. Honeywell, 2003. http://content.honeywell.com/vcsel/.
22. Optowell Co., 2000. http://optowell.com/homepage2/vcsel/SH85-2N001.pdf.
23. Light Reading, Inc, 2003. http://www.lightreading.com/document.asp?doc_id=3108&site=lightreading.