Designing digital optical computing systems: power distribution and cross talk

Jonathan P. Pratt and Vincent P. Heuring

Complex optical computer designs must implicitly or explicitly allow for power budgeting to compensate for cross talk and loss both in devices and in interconnections. We develop algorithms for calculating the system cross talk and power loss in optical systems by using a graph-theoretic model. Devices are modeled as directed graphs with nodes that represent inputs and outputs, and edges are weighted with the power relationships between nodes. Systems are modeled by interconnecting the individual device graphs in a manner that reflects the connectivity of the system. A system's power budget is efficiently computed by a depth-first search of its graph. The algorithms have been incorporated in an optical computer-aided design system that is presently being used to design a bit-serial optical computer that contains hundreds of components.

Key words: Optical computing, optical systems, optical communications, power loss, cross talk, graphs.

Introduction

We describe a technique that facilitates the design of digital optical computers and other complex optical circuitry, such as optical communications systems. Although there has been some discussion in the literature on power budgeting in optical systems, the treatment has been limited to relatively uncomplicated applications, in which heuristics and simple analysis are sufficient to estimate the power loss and cross talk of the system from the loss and cross talk of individual components. The primary motivation for this research is to implement a stored-program bit-serial optical computer, that contains hundreds of components interconnected in a quite complex fashion. In such a system, simple heuristics for power loss and cross talk estimation such as described in Refs. 1 and 2 are inadequate because a given optical signal might take any one of a multitude of paths before being detected and thus doing useful work. The methods developed here are applicable to a wide variety of optical systems besides optical computing systems, such as optical communications systems and optical signal processors.

Previously, we discussed the use of a graph-theoretic technique for synchronizing optical systems that rely on time of flight rather than latching or gating for synchronization. Here we extend these graph-theoretic methods to the estimation of cross talk and loss in optical systems.

Power Loss and Cross Talk in the System

Introduction

Appropriate signal levels must be maintained in any digital optical system that uses signal level thresholds to encode transmitted information. Usually a high-level signal represents a logic 1 and a low-level signal represents a logic 0. In these systems the device characteristics of importance are power loss and cross talk. Power loss quantifies the attenuation of optical power in devices. Cross talk represents the addition of extraneous optical power to signals transmitted by these devices. Thus the detection and the correct interpretation of power-encoded data are essential to correct system operation. The power loss and cross talk in optical devices add an additional level of complexity to the task of designing a system for a given functionality. Not only must a system be logically correct, it must also preserve the integrity of internally transmitted data. With significant amounts of power loss or cross talk or both, power-regenerating entities must be employed to restore
power levels and to minimize cross talk. Power loss and cross talk may be determined experimentally or obtained from the manufacturer's data. In either case, if a range of device performance is observed, the most pessimistic values should be assumed when calculating system performance with the equations below.

We present a graph-theoretic device model that permits efficient and complete power analysis of optical systems. By tracking certain power-related quantities, we can determine the worst-case operating conditions of a system, and optimal logic thresholds can be computed. The following discussion assumes that either loss and cross talk are independent of wavelength, or that linewidths are small enough to ignore these variations.

Power Levels and Correct Device Operation

Here we discuss the type of power information that is desired from a system model. Since the objective is to find weak points in the system power flow, only power extremes are considered. Power extremes are the cross talk and signal levels obtained when the worst possible combinations of device states and input power levels are assumed. The power extremes at detection points are of particular interest, because these are the locations where design flaws are evident through signal misinterpretation. Detection points are places where signal power is interpreted. Detection points in a system may be control points where the signal level is used to control a device; at the input to a logic gate, for example. Or they may be output points where the power level is detected and conveyed to an output subsystem as a data stream. This distinction is irrelevant here, and we refer to detection points in both of these cases.

Consider the problem of correctly interpreting a bit stream at some arbitrary detection point. Figure 1 depicts a stream of 1's and 0's arriving at a detection point. \( P_0 \) represents the power detection threshold of the detector: that power level below which the detector detects a 0, and above which it detects a 1. \( P_{Si} \) and \( P_{S2} \) define a safety zone around \( P_D \). They are based on the uncertainty in \( P_D \); they are established so that the chance of erroneous signal interpretation is negligible. By definition, the device operates correctly as long as all 1's arriving at the detection point have power levels greater than \( P_{Si} \), and as long as all 0's arriving at the detection point have power levels less than \( P_{S2} \). The weakest 1 arriving at the detection point under all conditions from all possible paths to the point is defined as \( P_{min} \), and similarly, the strongest 0 is defined as \( P_{0max} \). Proper device operation can be ensured if the following relations are met:

\[
P_{0max} < P_{S2} < P_D < P_{Si} < P_{min}.
\]

It is also desirable to have information about \( P_{max} \), the maximum power level that can occur at the inputs to a given device. A power detector may provide erroneous results when the power of a logic 1 arriving at a detection point is too large; that is, when \( P_{max} \) exceeds \( P_D \) by some large amount. A second and more important reason for computing \( P_{max} \) is that it makes the major contribution to cross talk, as discussed below. Knowledge of the power triple \( P_{0max}, P_{min}, \) and \( P_{max} \) at each device in a system permits the tracking of power levels throughout the entire system.

Modeling the Device

Here we discuss the means for calculating the power triples \( P_{0max}, P_{min} \) and \( P_{max} \) at the outputs of a given device, given the values of the triples at each of its inputs. We use a graph-theoretic model for the device. The main interest in the three signal power extremes is at the detection points; that is, points where the received power is dissipated during the signal detection process rather than transmitted through the device. When the appropriate device model is used, \( P_{0max}, P_{min} \) and \( P_{max} \) can be computed for each signal entering and leaving a device.

Figure 2 shows the device model that we employ in the computation. The model assumes that a device has \( n \) transmitting inputs that are coupled to \( m \) outputs with \( k \)-independent connection states. The states are selected by \( p \) inputs, which are detection points. In practice these detection inputs control the device states. Device inputs and outputs are treated as vertices in a graph, and the \( mn \) coupling terms correspond to edges. For each state of the device, weights are assigned to the edges that correspond to the loss or cross talk in the coupling in a given state. Gains are represented by negative losses. Thus for each state, each edge represents either the path of a desired signal through the device or the path of an unwanted signal through the device. There is a set of \( k \) \( mn \) coupling terms for each device.

This model assumes that loss and cross talk are linear phenomena. If this is not the case, as with fiber amplifiers, for example, then the equations for

---

**Fig. 1.** Power fluctuations at a detection plant.

**Fig. 2.** General device model.
the power triples below should be modified to incorporate the nonlinear behavior of the devices. Such a modification should not be particularly difficult if the transfer functions of the devices are known.

The power triple for the \( j \)th output of a device is computed from the input triples and the coupling terms as follows:

\[
P_{\text{min}}(\text{out})_j = \min_{s \in \text{states}_{\text{input}}} \left[ \min_{i \in \text{inputs}} \left[ P_{\text{min}}(\text{in})_i - L_q(s) \right] \right],
\]

\[
L_q(s) \in \text{loss}, \tag{2}
\]

\[
P_{\text{max}}(\text{out})_j = \max_{s \in \text{states}_{\text{input}}} \sum_{i \in \text{inputs}} P_{\text{max}}(\text{in})_i - L_q(s),
\]

\[
L_q(s) \in \text{cross talk},
\]

\[
P_{\text{max}}(\text{out})_j = \max_{s \in \text{states}_{\text{input}}} \sum_{i \in \text{inputs}} P_{\text{max}}(\text{in})_i - L_q(s). \tag{4}
\]

Equation 2 states that the power of the minimum 1 emerging from the \( j \)th output of the device is the minimum over all possible states of the minimum over all possible inputs that have loss terms of the minimum 1's arriving at those inputs minus the loss terms. Equation 3 states that the power of the maximum 0 emerging from the \( j \)th output of the device is the maximum over all possible states of the sum of either the inputs of \( P_{\text{max}} \) minus the cross-talk term for those inputs that have cross-talk terms in that state or \( P_{\text{max}} \) minus the loss term for those inputs that have loss terms in the particular state. Equation 4 states that \( P_{\text{max}} \) emerging from the \( j \)th output of the device is the maximum over all the possible states of the sum over all the inputs of \( P_{\text{max}} \) minus the loss or cross talk between each of those inputs and the output \( j \). These equations are in representational format, as the subtraction of the loss parameters implies logarithmic units for power; so in practice the summations require conversion to linear units. The loss and cross-talk terms \( L_q \) are the edge weights mentioned above. Note that circuit heuristics are ignored because the extremes are taken over all device states. That is, the power triple is guaranteed to be a bound on the worst case; but in a circuit, the worst case may not be as poor as the triple owing to the exclusion of some combinations of states and inputs. Equation 3 shows the most important reason for tracking \( P_{\text{max}} \): the greatest power produces the largest possible cross-talk term in this model. Thus \( P_{\text{max}} \) is essential for calculating subsequent \( P_{\text{out}} \) terms.

As example system components, consider lithium niobate directional couplers and passive 3-dB couplers as logic devices and optical fiber and 3-dB splitters for interconnection. Figure 3 shows a lithium niobate directional coupler configured as a fiveterminal optical device. Of the three device inputs \( a, b, \) and \( c \), only the first two are transmitting inputs that couple power directly to the outputs. Input \( c \), a detection point in our terminology, functions as a device control. As the logic equations show, when sufficient power is applied to \( c \), the switch is placed in the bar state; otherwise it is in the cross state. The graph model on the right of the figure makes \( c \) into a detection point that is independent of the two-state coupling between the other inputs and outputs. Figure 4 illustrates at a more functional level how the transmission coupling occurs.

3-dB couplers and splitters are modeled as devices with two inputs and two outputs, with 3 dB of loss from each input to each output, no cross talk, a single device state, and no detection points. Lossy interconnections, such as optical fibers, are modeled as devices with one input, one output, a single loss term, no cross talk, a single device state, and no detection points. There is no need to model loss-free interconnections, since they add nothing to the analysis. However, if it is desired to model them for clarity, or if a graphical system model already exists that contains them, they may be modeled exactly like lossy interconnections, but with zero loss and cross talk.

Modeling the System

Here we extend the applicability of the device graph model to complete systems. We demonstrated above that the power output triples can be computed for device outputs when the input triples are available. To track the triples in a complex system, we can construct a directed graph from the individual device models in a manner that reflects the connectivity of the system.

![Diagram and Logic](Diagram) ![Graph Model](Graph)

**Fig. 3.** Model of a lithium niobate switch.

**Fig. 4.** Illustration of loss and cross talk in a lithium niobate switch, where \( P \) is power (dBm), \( L \) is loss (dB), \( XC \) is cross-talk coupling (dB), and \( X \) is cross-talk power (dBm).
Two simplifying assumptions are made about the directed graph system model. The first assumption is that there is one power source only, and it is located at the root of the graph. This is not restrictive, because multiple sources are easily represented by coupling from the single source, with appropriate gains and losses introduced. As mentioned previously, negative loss is gain, and this is not ruled out in weighting the graph edges.

The second assumption is that the directed graph is acyclic; nowhere is it possible for a power transmission path to go full circle. It is possible to design optical systems that do not conform to this assumption; however, these instances are rare since they rely on special circuit heuristics to avoid too much attenuation of a single before detection. This also is not restrictive, since cycle transmission paths can be modeled by unrolling them, similar to the loop unrolling techniques used in compiler optimization.

The tracking of the power triples begins at the root of the graph model; the root is the only location where the triple is initially defined: \( P_{\text{imin}} = P_{\text{imax}} \) and \( P_{\text{omin}} = 0 \). Determining the power triples at the detection points is a subproblem of generating the critical paths from the root to the detectors. Critical paths are those that result in the largest (or smallest) sum of edge weights when followed from the root to detection vertices.

The problem of finding critical paths is efficiently solvable with order \((n)\) depth-first search algorithms. The power triples are calculated by scanning the vertices in ascending order and by applying Eqs. (2), (3), and (4) to each.

When the search algorithm detects that the conditions of Eq. (1) are not met, it is desirable to know the critical path to the detector so that the problem can be corrected. This is accomplished by backtracking the power triples from the detection point. Because edges are contained within devices, backtracking along the critical path requires that critical device inputs be determined. The critical input is simply the one that produces the maximum (or minimum) term in the output power triple of interest. Note that the critical paths for \( P_{\text{imax}}, P_{\text{omin}} \), and \( P_{\text{imin}} \) are usually not the same. For \( P_{\text{imax}} \) and \( P_{\text{omin}} \), maximum values are tracked, whereas minimum terms are used to track \( P_{\text{imin}} \).

As an example, Fig. 5 illustrates a simple optical circuit and its graph model: two directional couplers and three 3-dB splitters, all of which are used to generate a timing signal. The switches employ the model of Fig. 3. The splitters are modeled as described above, and interconnecting fibers are shown for clarity, although they are assumed to be lossless. Vertex 1 of the model corresponds to the clock (CK) signal, which is also the root. The c inputs to the switches are detection points, labeled as D1 and D2 in the model. The vertices in the model have already been ordered by depth-first search algorithm so that a direct scan can be used. Consider the task of finding the \( P_{\text{imin}} \) terms and the critical paths associated with these terms. We assume the switch loss is 5 dB, the splitter loss is a balanced 3 dB, and the power source provides 0 dBm to each outgoing edge. The vertices are scanned in order to produce Table 1.

Note that the power level at detection point D1 (vertex 6) is found by taking the \( \min(-5 - 3, -8 - 3) = \min(-8, -11) = -11 \). The critical path for D1 is backtracked through vertices 5, 4, and 1. The only decision in this example is at vertex 6, where vertex 5 is chosen over vertex 8 because -11 is less than -8.

Discussion

The technique described above is indispensable in designing complex optical systems whose components have significant nonidealities. It has been incorporated into a digital optical computer-assisted design system, HATCH, in which it has proven invaluable in designing optical counters and an optical delay line memory system. It is presently being used in designing a bit-serial optical computer now under construction in our laboratories. The HATCH system is available in both Macintosh and X Windows versions upon request to the Optoelectronic Computing Systems Center.

<table>
<thead>
<tr>
<th>Vertex</th>
<th>( P_{\text{imin}} ) (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-3</td>
</tr>
<tr>
<td>3</td>
<td>-5</td>
</tr>
<tr>
<td>4</td>
<td>-5</td>
</tr>
<tr>
<td>5</td>
<td>-8</td>
</tr>
<tr>
<td>6</td>
<td>-11</td>
</tr>
<tr>
<td>7</td>
<td>-8</td>
</tr>
</tbody>
</table>
Several extensions of the technique would be useful. Extending the method to determine optimal placements for power regenerating circuitry would be quite useful in automating the process of adding power regeneration nodes. This extension might involve the development of algorithms that iteratively perturb a system architecture and act on the results of the power characterization to minimize the cost of the additional circuitry.

As we mentioned above, linear cross talk and loss behaviors are assumed in the device models for computing the power triples. If the transfer functions of the devices are nonlinear, then the three equations should be modified to incorporate the appropriate transfer characteristics.

This research was supported by the National Science Foundation Engineering Research Centers program under grant CDR 8622236 and by the Colorado Advanced Technology Institute.

References