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# NEMI Cost Analysis: Optical Versus Copper Backplanes

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**Abstract**
The outlook for optical PCBs is unclear for mainly three reasons: 1) today's limits for copper boards can be stretched with design and manufacturing improvements, 2) the market demand for next generation, higher bandwidth telecom systems (in the 40Gbps range) won't be clearly known for years, and 3) the point at which optical backplanes cost less than copper backplanes depends on many unknowns, including the type of optical technology, the design issues (such as layer count), and the ever-important manufacturing yields. Focusing on issue number three, a NEMI project seeks the answer to the question, "Under what conditions does optical cost less?" This paper reviews the analysis so far, including major cost model manufacturing assumptions, design factors, and choices of optical technologies.

**Introduction**
While electronics continually advances in the face of increased performance requirements, the industry is debating the limits of the electron.[1] Starting with high-end telecom systems as one frontier pushing the bandwidth limits of copper, this NEMI team has focused on the backplane – the crossroads for signals being switched between an array of daughter cards. The maximum capability of the backplane determines the performance of the system, in this case measured as high as about ten gigabits per second (Gbps) of switching capacity. Within today's backplane, we see layers of copper, whose characteristics mostly determine how many Gbps we can switch.

"Going faster" in a copper backplane entails any combination of the following:
- Making the copper thicker
- Making the dielectric layer thinner
- Using dielectrics with lower loss tangents
- Adding more signal layers
- Minimizing the signal length
- Maximizing distance between signals
- Making the board larger (wider and longer) to handle more signals per layer

Meanwhile, we observe that a single optical fiber has a far higher transfer rate in Gbps than a whole copper backplane. Why not make the backplane out of fiber? Today, some backplanes have a surface layer of fiber, so that is certainly possible.[2] But these fibers provide point-to-point connections, not true bus-based backplane performance. Further, the cost can be enormous, since each fiber end needs to be connected to a unique optical module, or spliced to another fiber, entailing assembly time and module costs.

But, there are other ways to carry photons. Optical waveguide research holds the promise of electronic-like circuit board structures, complete with optical vias, patternable signal layers, bus architecture, and simple assembly methods.[3] However, this technology leap requires complementary developments, including new connectors (optical), optical modules with laser and detector arrays that align with optical vias, and turning light at a 90-degree angle. Most of these technology hurdles have been proven in the lab at this time. Whether they can be commercialized depends on a number of factors, including the following:

- Market need for optical performance levels
- Manufacturability
- Reliability
- Connector cost
- Assembly cost
- Optical PCB cost

The NEMI optical PCB cost modeling project is focusing on this last issue, as an extension of prior NEMI project work.[4] It's a "what-if" analysis: "What if there's a market need? Before we go testing reliability and working out the manufacturing scale-up issues, we need to know the cost relationship."

To this end, the NEMI team has developed a copper-based backplane cost model as a starting point. The team has validated the model with two medium-sized US PCB companies familiar with the backplane business, along with two North American telecommunication system OEMs who routinely purchase backplanes.

This paper shows the initial results of the copper backplane model. However, comparisons to optical PCBs are not yet undertaken. Stumbling blocks to such an analysis are being addressed by the NEMI team, and include the following:

- What metric should be used when comparing copper and optical circuit boards?
- What optical PCB technology(ies) should be considered

The cost comparison goal is to show a cost-performance crossover point, highlighting where optical PCBs would be more cost effective than copper, such as the conceptual graph in Figure 1.

Figure 1 also raises the question as to how the technologies will be compared. By PCB? By channel? A few cost-performance metrics for comparing optical and copper PCBs are the following:

- Cost per Gbps per top surface square inch: takes into account the number of metal layers (not including ground/power planes), maximum Gbps per channel, and maximum channels per inch (as determined by minimum line/space rules)
- Cost per Gbps per channel per meter: takes into account losses per unit length and maximum Gbps per channel
- Cost per Gbps per board: takes into account design-dependent maximum Gbps for all channels on the board at any one time
- Cost per Gbps per board cross-section: takes into account maximum Gbps per channel and the number of channels cut by a cross-section dividing the length of the board into equal parts.

Given the widely different possibilities in cost-performance metrics, and given the importance of this metric in defining a cost crossover point, the NEMI team needs feedback on the merits of these and other potential metrics.

As a result of the many questions to be answered by the NEMI team, this paper shows progress to date on the copper backplane model and reviews the optical PCB technologies under consideration for future analysis.

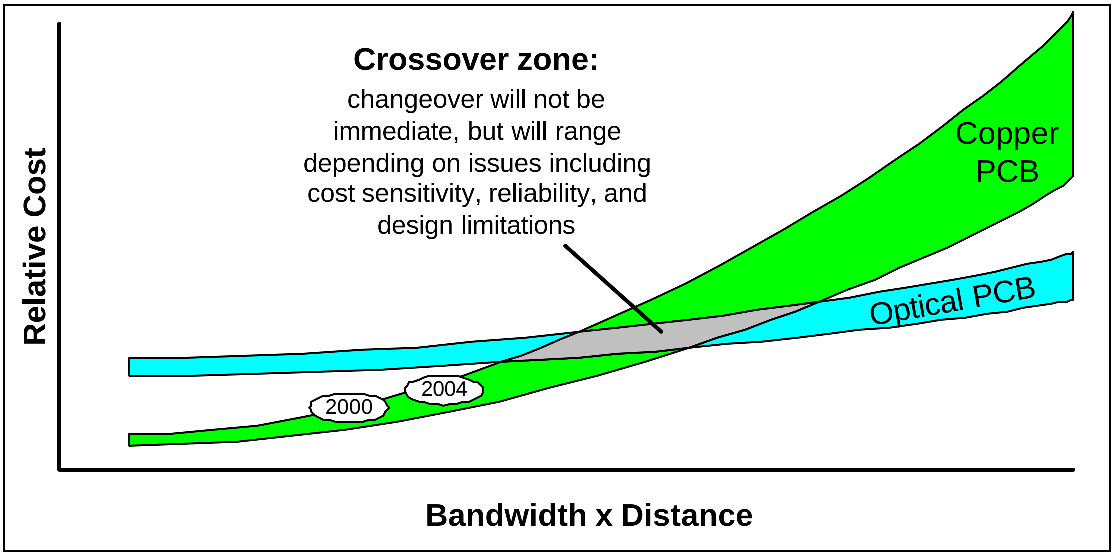


**Figure 1 - The NEMI Cost Modeling Goal is to Find the Crossover Point between Copper and Optical PCBs**

## Background on Manufacturing Models

### *Cost Models*

A cost model attempts to capture the manufacturing cost of producing an item. Its purpose can vary widely, such as for guiding pricing, assisting purchasing, speeding design, directing marketing strategy, and answering capital investment decisions. Cost models can differ in many ways:

- Scope: what operations are covered. For instance, does the cost include indirect processes like design or recycle?
- Method: how the costs are calculated. For instance, are the costs calculated based on knowledge of each step (e.g., activities based costing, or "bottoms up") or based on historical accounting numbers for the facility (e.g., "top down").
- Engineering relationships: how predictive the model is. Cost models can include equations that relate product design inputs to operating time, tooling costs, process flow, and many others.
- Purchasing impact: for operations where component purchasing cost makes up most of the manufacturing cost (i.e., board assembly), the model may simply be an up-to-date inventory of parts, allowing the designer to use the optimal combination of parts for reducing the bill of materials.

Key output metrics for a cost model are the finished cost per part, the part cost breakdown by cost element (materials, labor, equipment amortization, and so on), and the part cost breakdown by operation.

### *Pricing Models*

Pricing models typically help guide the quoting efforts of a sales team. These are often based on rules of thumb. For instance, from an accounting (top down) perspective, a company may know that it costs X for a 4 metal layer PCB panel that's 18 inches by 24 inches, at so many pieces per month. This cost might be adjusted by design and yield tradeoffs for characteristics such as the number and size of drilled holes, linewidth and spacing, volume, and so on. They then figure out how many boards they can fit on the panel. Finally, they add in a margin to cover overhead and profit. This method is limited by the historical data set, since its relationships are usually based on historical accounting data. Also, this method likely misses interactions between factors. For instance, if the rule says add $10/panel for every 1,000 drilled through-holes, how accurate will that be for thin versus thick laminates? Alternatively, pricing models can be quite complex, derived from bottoms-up engineering relationships – in other words, a cost model with margin factored in.

Key metrics in a pricing model are the price per part at different volumes, and with various design options or materials as customer discussions have dictated.

### *Business Models*

Business model are usually implemented when someone having access to millions of dollars is contemplating investing in new products (new to a market or new to a company). In such a case, the projected revenue stream is superimposed on a projected cost schedule. The revenue stream can be quite complex on its own, and may include S-curve models for the penetration of new technologies and market share estimates based on conjoint analysis (complex surveys that attempt to determine customer-perceived value as a function of product performance). Also, the revenue stream can include pricing assumptions over time.

The cost schedule usually reflects total facility cost, not unit product cost, so that the costs of running a business are modeled. Modeling capital outlays over time is a critical requirement for a cost model used within a business model. To this end, the cost model needs to incorporate the productivity of each machine, so that, as volumes increase, the user knows how many machines are needed. Further, the scope of the cost model should be wider for modeling a business. For instance, manufacturing cost models don't usually include the sales force, designers, administrative offices, distributor charges, and so on. But, a business model needs to capture such indirect costs.

Key metrics for a business model are time to breakeven and to profitability, return on investment, net present value, internal rate of return, and many variations on these.

**Modeling Manufacturing Cost - Technical Cost Modeling**

An extension of activities based costing, the Technical Cost Model as developed by IBIS Associates seeks to maximize the number of predictive engineering relationships (5). In other words, the product design, material choices, and manufacturing processing techniques are interdependent in real life. A cost model can be invaluable if it robustly captures such dynamics. The NEMI cost model implements a tool that captures some of these dynamics. (See Figure 2.)

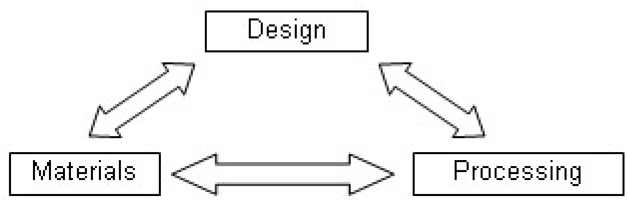


**Figure 2 - Manufacturing Interdependencies Common in Reality, as well as in a Well-Built Cost Model**

**Predictive Relationships in the NEMI Model**

Just about all cost factors in an operation are tied to its cycle time. Product materials (e.g., laminates) and tooling (e.g., drill bits) are not affected by cycle time in most cases. But, process material (e.g., nitrogen), labor, utilities, building, equipment amortization, and related equipment issues (e.g., maintenance) vary directly with cycle time, on a cost-per-product basis. As a result, it's important that cycle time for an operation be as accurate as possible. If possible, the cycle time should be a calculation based on design, materials choices, and the limitations of the process equipment. (See Figure 3.)

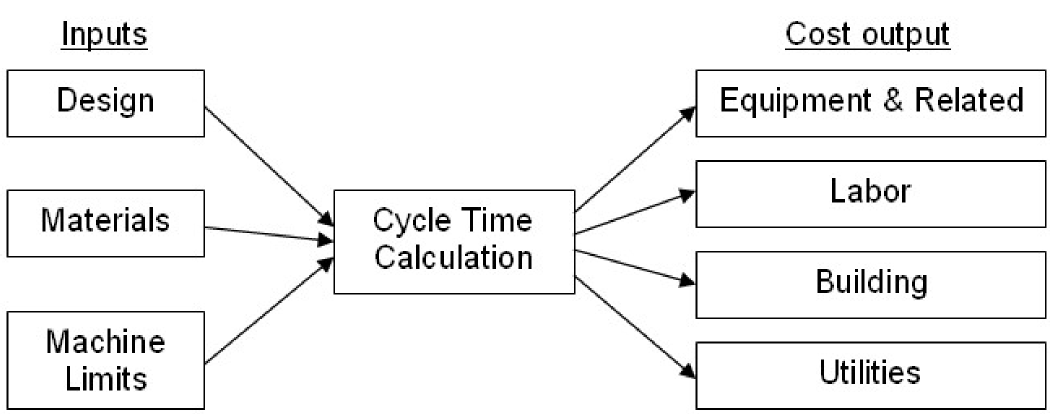


**Figure 3 - It's Critical to Model the Cycle Time as Accurately as Possible, by Capturing how Specific Inputs affect Operation Processing Time**

**Unique Aspects of the NEMI Model**

With the NEMI copper backplane cost model, the team has modeled a medium-sized facility (350K sqft per year top surface output) in North America. Equipment pricing reflects this scale, as well as a maximum 24 inches of panel width. Yields for the innerlayers are reflective of 8 mil lines and spaces. Drilling time and drill bit prices reflect a minimum hole diameter of 20 mils.

For now the model only predicts the cycle time for the drilling and hole inspection steps (as a function of the number of through holes). Other operations depend on input from the NEMI team.

***PCB Design Inputs***

The backplane design reflects an "average" backplane, but will be adjusted to model an actual design once an OEM contributes one of their designs to the team. For now, the PCB has the following characteristics:

- 20 inch width
- 24 inch length
- 8 mil lines and spaces
- 20 mil minimum through-hole diameter
- 5,000 through holes (no buried or blind vias)
- 32 metal layers
- All FR-4 laminates
- Innerlayer yield of 94% per innerlayer pair results in a final yield of 88%

***Facilities Inputs***

Figure 4 lists the inputs relating to the facility, showing the North American labor rates, electricity cost, working days, and depreciation schedule.

| | | |
|---|---|---|
| Direct Labor Wage | $15.00 | /hour |
| Indirect Labor Salary | $50,000 | /year |
| Indirect Laborers:Direct Laborer Ratio | 0.07 | ilab/dlab |
| Indirect Labor Shifts per Day | 1.2 | shift/day |
| Benefits on Wage/Salary | 35.0% | |
| Working Days per Year | 360 | d/yr |
| Working Hours per Day | 24 | h/d |
| Capital Recovery Rate | 8% | /yr |
| Working Capital Period | 1 | mo(s) |
| Equipment Depreciation Life | 5 | yrs |
| Building Recovery Life | 20 | yrs |
| Total Space:Work Space Ratio | 1.25 | : 1 |
| Price of Electricity | $0.110 | /kWh |
| Dedicated Equipment? | 0 | [1=Y 0=N] |
| Equipment Investment Scaling Factor | 100% | of baseline |
| Non-Recurring Engineering | $1,000 | per design |

**Figure 4 - Facilities Inputs for the NEMI Cost Model**

***Operation Flow***

The innerlayers are processed with the following sequence of steps:

- Receive Laminate
- Clean - Chemical
- Laminate Dry Film
- Expose Dry Film
- Photo Plotter
- Develop Dry Film
- Etch Cu - Strip Resist
- Film Punch
- Registration Punch
- AOI
- Oxide Coating System

The outerlayers see the following sequence of steps:
- Receive Prepreg
- Receive Foil
- Kitting and Lay-up Area
- Laminate Multilayer (Press)
- Routing - Depin and Debook
- Deflash & ID
- Pin Stack - Before Drill
- Drill Through Holes
- Deburring
- Auto Hole Check
- Desmear & Etchback - PM
- Plate E'less Cu
- E'lytic Strike Cu
- Clean - Pumice Scrub
- Laminate Dry Film
- Expose Dry Film
- Photo Plotter
- Develop Dry Film
- Plate E'lytic Cu & Sn
- Strip Resist, Etch Cu, Strip Sn
- Manual Hole Size Check
- AOI
- Repair Opens & Shorts
- Clean - Chemical
- Flood Coat Solder Mask (DS Screening)
- Tack Cure
- Expose Solder Mask
- Develop Solder Mask
- UV Cure
- Cure
- HASL & Clean
- Nomenclature Print
- Routing - Depaneling
- Clean
- Electrical Test
- Flying Probe
- Find, Analyze, Repair, Retest
- Final Inspection & Audit
- Clean
- Final packaging & labeling

***Model Output***

For the copper backplane base case, the cost of the PCB ($560 per PCB) was within a margin of 10% according to the PCB fabricators on the NEMI team. Figure 5 reveals the costs and the cost breakdown by contributing elements.

Most of the cost is accounted for by raw materials (mainly laminates), followed by labor (Dir=direct and Ind=indirect) and equipment costs.

| Cost Summary (per board) | | | | |
|---|---|---|---|---|
| Innerlayer Cost | $416 | 74% | Total Equipment Investment | $44.0 MM |
| Outerlayer Cost | $144 | 26% | Total Building Space | 23.0 K sqft |
| *Total Cost* | *$560* | | Total Building Investment | $2.1 MM |
| Cost/Sqin (Top Surface, Board) | $1.55 | | | |
| Cost/Sqin (Top Surface, Panel) | $1.17 | | | |
| Cost/Sqin (Per Metal Layer) | $0.036 | | | |

**Cost Factor Breakdown (per board)**

| | ***Dir Labor*** | ***Material*** | ***Utilities*** | ***Tooling*** | ***Equip*** | ***Bldg*** | ***Ind Labor*** | ***Maint*** | ***Capital*** |
|---|---|---|---|---|---|---|---|---|---|
| Innerlayer Cost | $86 | $258 | $2 | $10 | $34 | $0 | $9 | $7 | $10 |
| *% of innerlayer* | *21%* | *62%* | *0%* | *2%* | *8%* | *0%* | *2%* | *2%* | *2%* |
| Outerlayer Cost | $33 | $49 | $1 | $18 | $25 | $0 | $5 | $5 | $7 |
| *% of outerlayer* | *23%* | *34%* | *1%* | *13%* | *18%* | *0%* | *4%* | *4%* | *5%* |
| **Total Cost** | **$119** | **$307** | **$3** | **$28** | **$59** | **$1** | **$14** | **$12** | **$17** |
| *% of total* | *21%* | *55%* | *1%* | *5%* | *11%* | *0%* | *2%* | *2%* | *3%* |

**Figure 5 - Cost Output from the NEMI Optical Backplane Cost Model**

### *Analysis*

Figure 6 supposes that the hole counts and layer counts are either too high or too low compared to the "average" copper backplane. What is the impact of changes in the number of holes and metal layers on cost? Lower layer count and hole count leads to a cost 26% lower than the base case, while increasing layer count and hole count adds 19% in cost. In other words, assuming the "average" backplane produced today is within this range of hole and layer counts, its cost will range from $411 to $668.

| | No. of Drilled Holes | No. of Metal Layers | Post Lam'n Yield | **Total Board Cost** | Cost per Board Metal Layer | Cost per Top Panel Surface Sqin | Cost per Top Panel Surface Sqin Metal Lyr | Total Equipment Invest (MM) | Total Building Space (Ksqft) |
|---|---|---|---|---|---|---|---|---|---|
| Baseline Case | 5,000 | 32 | 88% | **$560** | $17.49 | $1.17 | $0.036 | $44 | 23.0 |
| Holes Lower | **2,500** | 32 | 88% | **$545** | $17 | $1.14 | $0.036 | $43 | 22.1 |
| Holes Higher | **7,500** | 32 | 88% | **$574** | $17.94 | $1.20 | $0.037 | $45 | 24.2 |
| Holes Highest | **10,000** | 32 | 88% | **$588** | $18.39 | $1.23 | $0.038 | $46 | 25.1 |
| Layers Lower | 5,000 | **24** | 91% | **$423** | $17.61 | $0.88 | $0.037 | $38 | 20.0 |
| Layers Higher | 5,000 | **36** | 86% | **$634** | $17.61 | $1.32 | $0.037 | $47 | 24.4 |
| Holes & Layers Lowest | **2,500** | **24** | 91% | **$411** | $17.14 | $0.86 | $0.036 | $37 | 19.1 |
| Holes & Layers Highest | **10,000** | **36** | 86% | **$668** | $18.56 | $1.39 | $0.039 | $49 | 26.5 |

**Figure 6 - Cost Variation Based on Changes to the Hole Count, Layer Count, and Yield**

## Further work

### *Copper Backplane*

The NEMI team intends to settle on an actual design, or emulator, for our baseline case going forward. Further, the team needs some next -generation designs to plot the future cost of copper.

### *Optical Backplane*

Considering only the PCB, there are a number of technology choices for this modeling exercise:

- Embedded waveguide edge-coupled. This approach would connect the optical layer(s) to the optical modules at the edge of the board.
- Embedded waveguide surface coupled, requires out-of-plane bend. This technology would have optical modules on the surface of the board, as with SMT components.
  - Mirror or grating, embedded, or on support/connector (in via)
  - Bent waveguide
  - Other

Further work will most likely focus on a couple of the alternatives, since optical backplanes will likely happen in stages.

***Toward Predictive Relationships for the Performance Metric***

If possible, given enough accurate "design rules of thumb" for copper and optical PCBs, the models should eventually calculate cost model design inputs (e.g., number of holes, PCB length and width, and so on) as a function of the performance metric (Gbps per channel per meter, Gbps per board, and so on). That way, the graph in Figure 1 could show crossover points as performance is driven beyond today's limits for copper, and into the zone where optical PCBs appear more competitive.

**Summary**

The NEMI optical backplane cost modeling team has developed the framework for comparing optical PCBs to today's copper PCBs. PCB fabricators and OEM users have validated the copper case output costs, ensuring the model is within 10% of their internal cost models.

Future work will involve the selection and modeling of an optical PCB or progression of optical PCB technology types.

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