Connectors

High speed connectors are expensive.

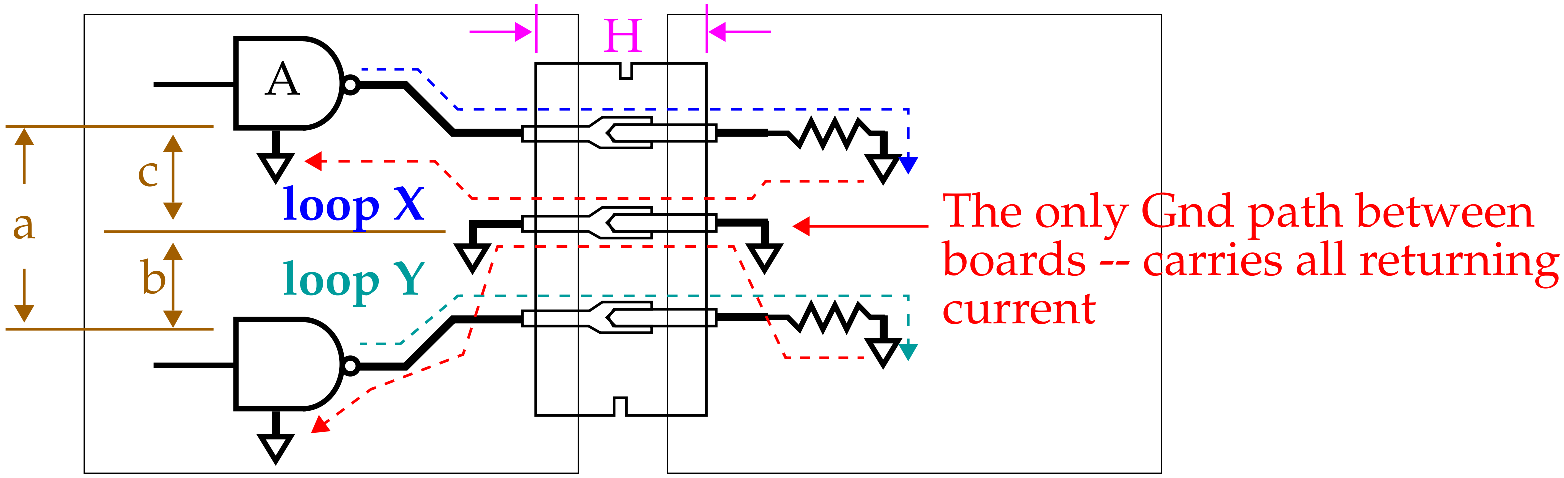
The DIN connector (good to few tens of MHz) costs **100 times less** than hand-assembled SMA hard line connectors (good to 25 GHz).

The performance altering characteristics of connectors include:

- Mutual inductance (causes crosstalk)
- Series inductance (slows signal propagation and generates EMI)
- Parasitic capacitance (slows signal propagation)

Mutual Inductance

Let's focus on how connectors create crosstalk.



The only Gnd path between boards -- carries all returning current

Mutual Inductance

The overlapping return path currents causes magnetic fields and introduces *noise voltages*.

Also note that connectors have parasitic capacitance between pins.

The crosstalk is usually less significant than inductive crosstalk (more on this later).

In order to approximate the amount of signal crosstalk, we need three things:

- The mutual inductance between two loops.
- The maximum rate of change of the source signal, dI/dt.
- The impedance of the receiving network and whether it is src- or end- terminated.

Magnetic flux in *loop Y* comes from two places.

- Signals flowing out of gate A.
- Returning signal currents in the ground wire.

It follows that the expression includes two terms to account for these srcs.

Mutual Inductance

The second term (ground wire term) in the mutual inductance equation is the larger of the two.

$$L_{X,\,Y} = 5.08H\ln\left(\frac{c}{a}\right) + 5.08H\ln\left(\frac{b}{D/2}\right)$$

a = distance of signal X from signal Y, in.
b = distance of signal Y to ground wire
c = distance of signal X to ground wire
D = diameter of connector pin
H = pin length in connector

This expression assumes a single row of pins and a relatively long connector (large H/a ratio).

If this is not true, the answer is still within an order of magnitude (because of the logarithm).

This is good enough to determine if the performance impact of the connector is significant.

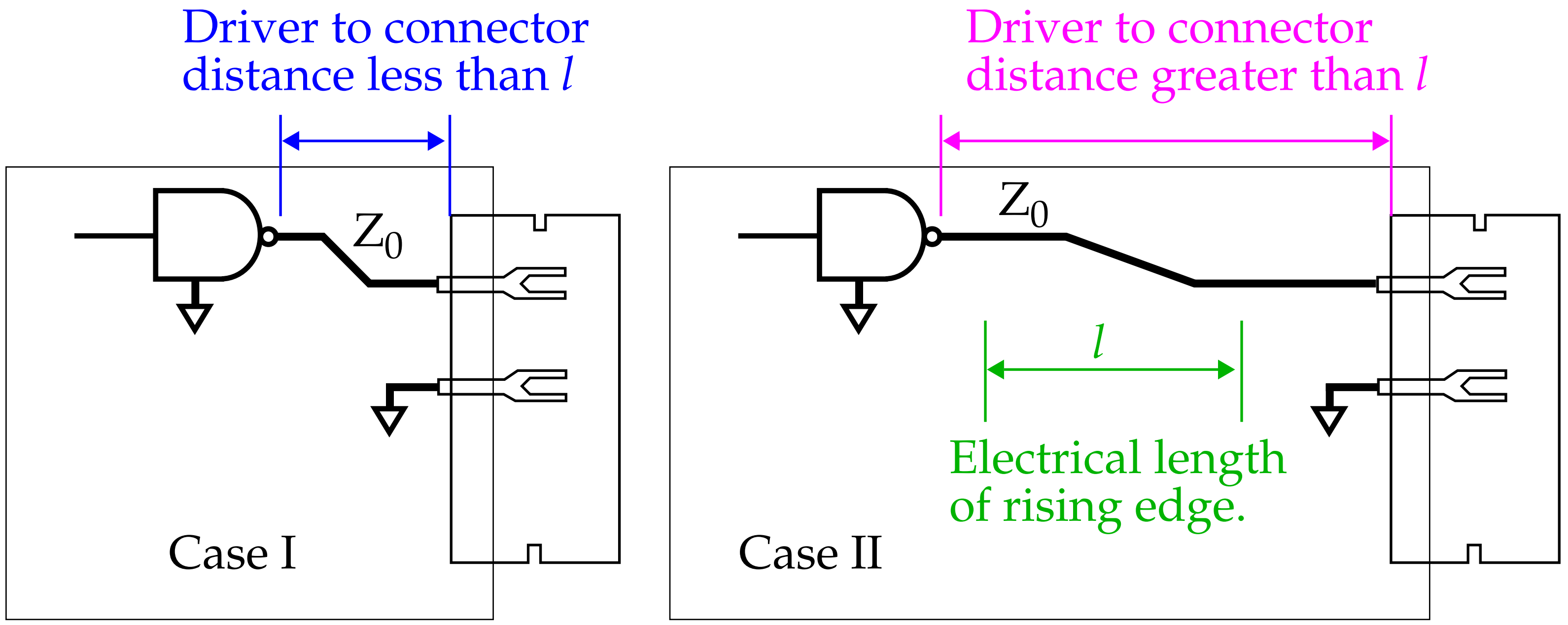
Mutual Inductance

Next we need the maximum dI/dt.

Our previous expressions work here:

$$\max \frac{dI}{dt}(\text{resistor}) = \frac{\Delta V}{T_{10\text{-}90}}\frac{1}{R} \qquad \max \frac{dI}{dt}(\text{cap}) = 1.52\left(\frac{\Delta V}{T^2_{10\text{-}90}}\right)C$$

The third item involves the topology of the loop Y.



Driver to connector distance less than l

Driver to connector distance greater than l

Electrical length of rising edge.

Mutual Inductance

The crosstalk (height of noise pulse in loop Y) for Case I is.

$$\text{Crosstalk} = L_{X,Y}\frac{dI}{dt}$$

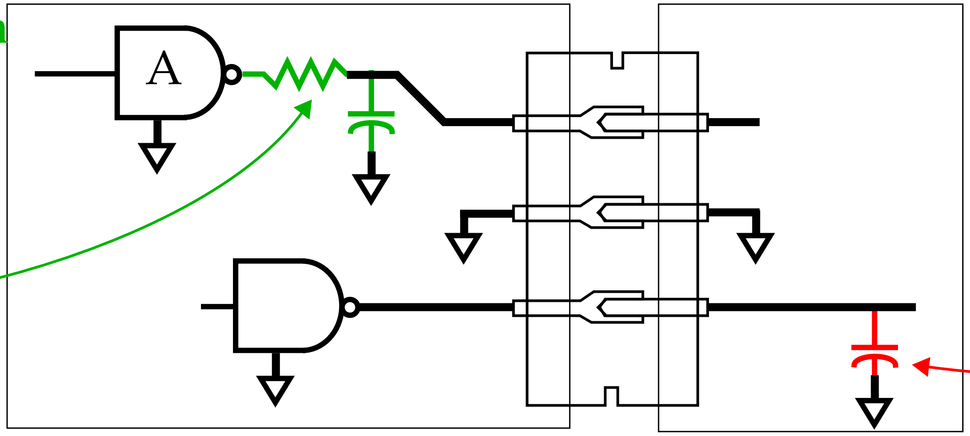
Here, the coupled noise reflects off the low-impedance driver, **doubling** the coupled noise on the receiving side.

For Case II, the coupled noise splits in half in either direction.

$$\text{Crosstalk} = \frac{1}{2}L_{X,Y}\frac{dI}{dt}$$

Slowing the rise time of the driver only moderately improves crosstalk.

A better solution



Any series resistance here, resistor or inductive bead, improves cap effectiveness

INCORRECT only increases surge current flowing through connector when driver switches

Ground Connection Arrangements

The previous equation and the following rules can help estimate the behavior of various connector grounding arrangements.

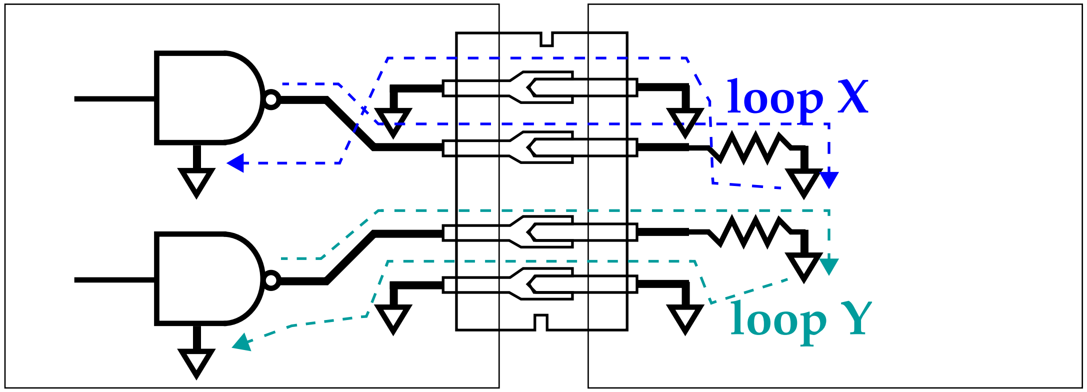
$$L_{X,\,Y} = 5.08H\ln\left(\frac{c}{a}\right) + 5.08H\ln\left(\frac{b}{D/2}\right)$$

- Moving the ground wire *closer/further* from signal wires X and Y, *decreases/increases* *b* and *c*, causing both terms to *shrink/grow*.

  The change in inductance is proportional to the *logarithm* of distance.

- Since the ground wire term is larger, adding extra ground pins has a large impact since it *decouples* the return currents.

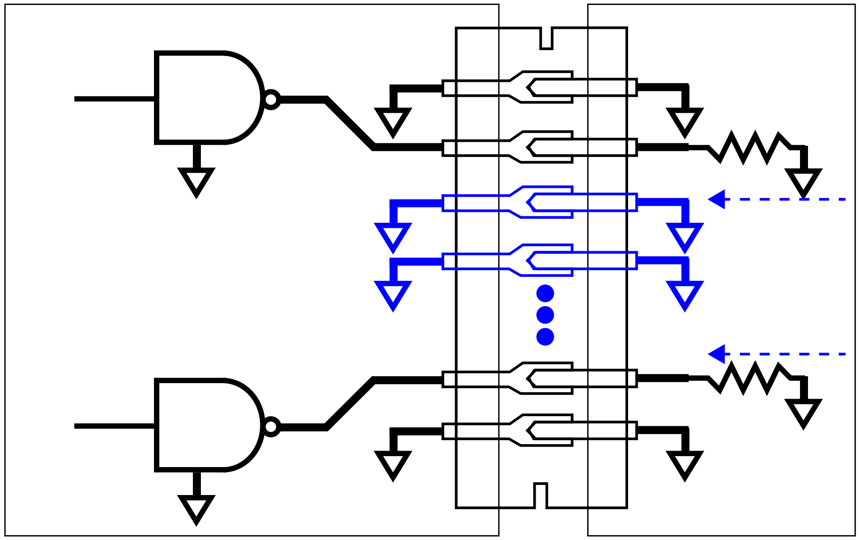
  Dividing the ground wire current in half nearly halves $L_{X,Y}$.



Ground Connection Arrangements

Note that adding more ground pins continues to split the ground current but is not nearly as effective as the first split by two.

- Interposing ground wires **between** signals X and Y makes a bigger difference than adding grounds outside of X and Y.



Adding N grounds between signals reduces coupling by a factor of

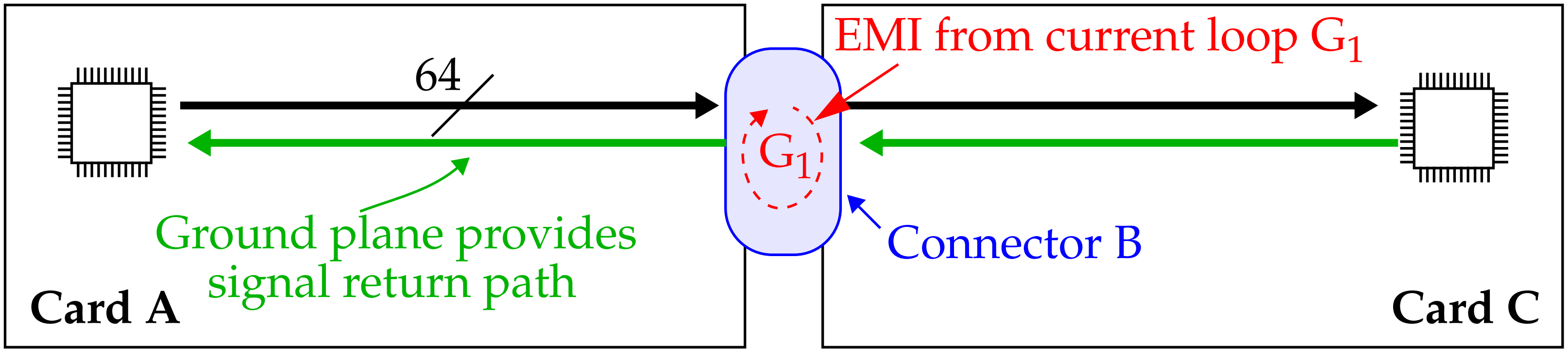
$$\frac{1}{1+N^2}$$

- Each of the wires in the connector couples noise, so simply reducing the number of signals in the connector cuts aggregate crosstalk.

As shown above, you can create *virtual* partitions within the connector using grounds that is nearly equivalent to using multiple connectors.

Series Inductance

Electromagnetic interference (EMI) emanates from signal current flowing in large loops.



Connector B provides ground pins for signal return current.

High frequency currents flowing in large loops radiate EM energy and will not pass FCC-mandated radiated emission tests.

Objective w.r.t. EMI is to contain all sign flow to small cross-sectional loops.

The ground loop on the cards above is small, e.g., 6 in. trace with 0.010 in. to ground plane yields a loop of 0.06 in^2.

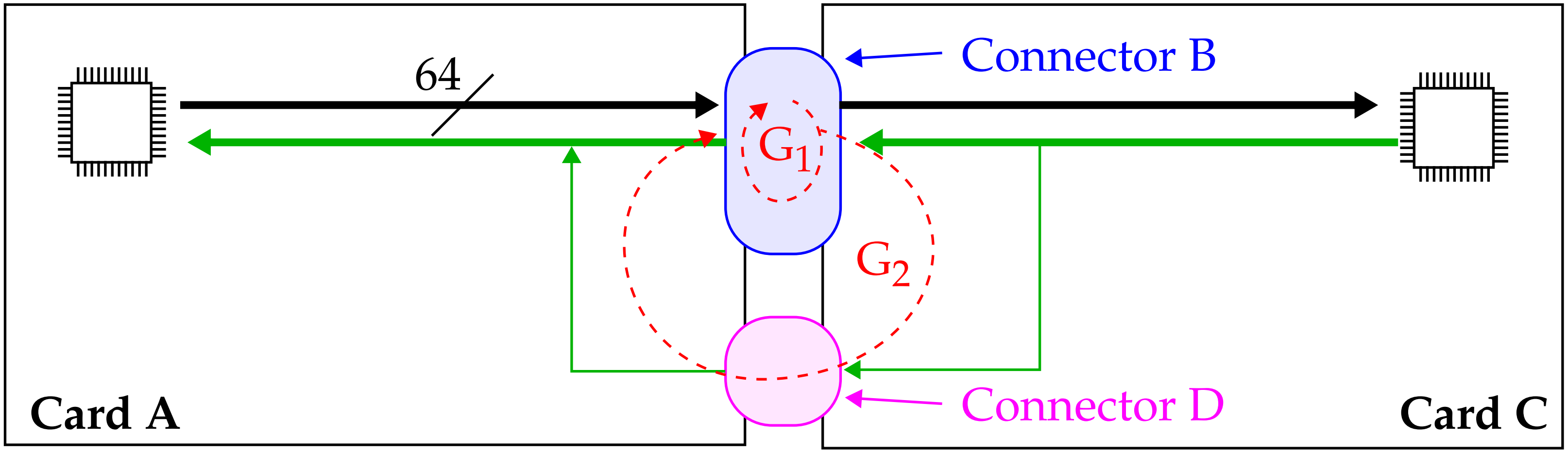
This can typically be ignored for EMI purposes.

Series Inductance

The interruption in the ground plane between the cards, however, creates a *bubble* in the current loop.

This occurs within the connector, labeled as loop G_1, which forces the signal and ground pins to separate.

Cards that provide alternative return paths are much worse.



The proportion of high speed current that flows through connector D depends on the ratio of loop inductances.

$$\text{Current through D} = (\text{return current from A})\frac{L_{G1}}{L_{G2}}$$

Series Inductance

Since G_1 is likely to much smaller than G_2, only a small fraction flows through connector D.

However, this can still pose a problem because above 30 MHz, FCC limits are approximately 100 μV/m (measured at 3 meters from equipment).

Calculating precise radiated intensity levels **is difficult** because of the multitude of variables.

This expression gives a simple restriction on *loop area*, *peak current* and *rise time* that should pass FCC limits above 30 MHz.

$$E = 1.4 \times 10^{-18} \frac{A I_p F_{clk}}{T_{10\text{-}90}} < 10^{-4} \text{ V/m}$$

E = radiated electric field, V/m, at 3 meters

A = radiating loop area, in^2.

I_p = peak current, A

$T_{10\text{-}90}$ and F_{clk} = signal rise time and clk frequency.

Series Inductance

Text works through an example that uses this expression.

Rules for reducing connector emissions:

- Use more grounds in connector B.

  This lowers the effective radiating loop area in connector B.

  This also reduces the inductance of connector B, reducing currents in remote loops.

- Disrupt or remove remote return paths by keeping all connections between cards A and C close together.

- Place a **continuous ground contact** along the entire edge of cards A and C.

  The low impedance return path lowers the *remote* loop current.

- Never attach I/O cables on the outer edge of card A.

  This creates a large remote return-current path from card C, through earth ground and back into card A through the I/O cable.

  Bypass them on card C near the connector B.

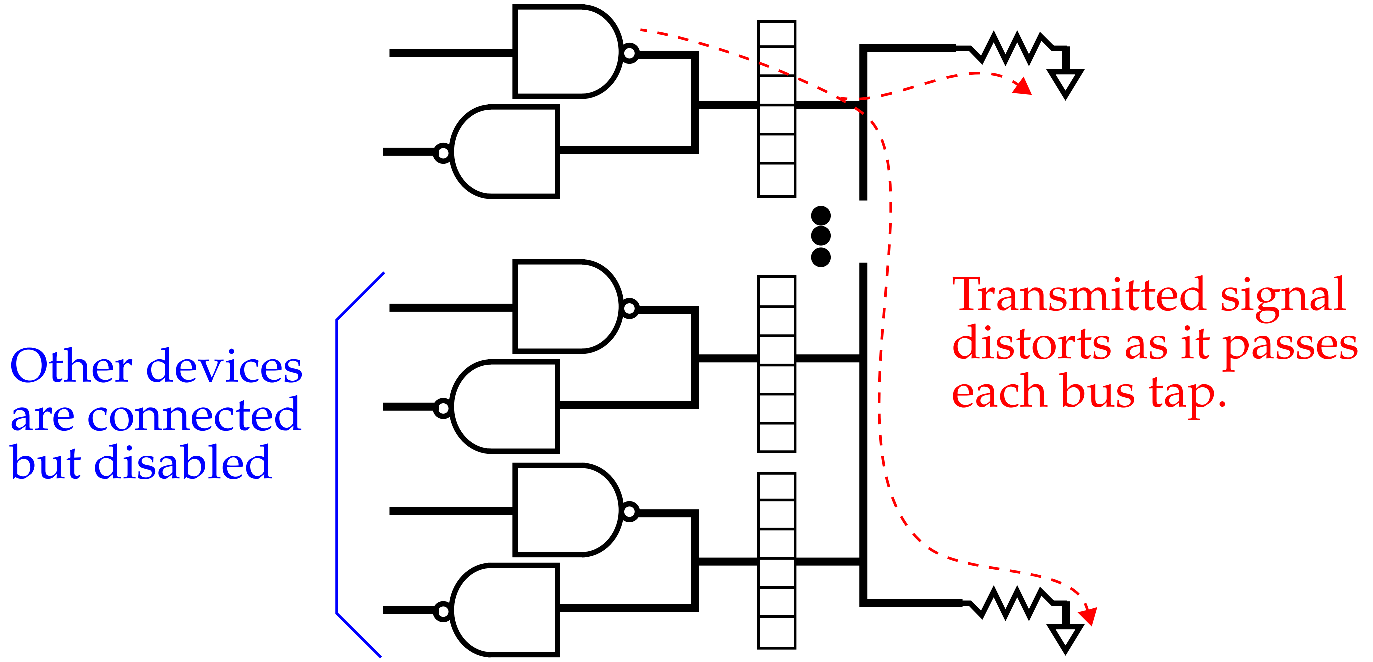
Parasitic Capacitance

We will focus here on **multidrop bus** applications rather than point-to-point applications.

In point-to-point, each signal traverses each connector only once.

Here the connectors series inductance dominates performance.

In contrast, the cumulative effect of parasitic capacitance from many connectors has a larger impact than series inductance in a multidrop bus.



Other devices are connected but disabled

Transmitted signal distorts as it passes each bus tap.

Parasitic Capacitance

Therefore, choose a connector with very low parasitic capacitance, even at the expense of higher inductance.

It is important to minimize the total *lumped capacitance* to ground at each tap.

The connector cap is only one portion of it.

The lumped capacitance consists of three parts.

- Pin-to-pin cap of the connector and its pads on the PCB.
- Cap of the trace to and from the drivers and receivers.
- Input cap of the local receiver and output cap of driver while disabled.

Pin-to-pin capacitance

This term is easy to measure by mounting the connector on a board and grounding all pins except a signal pin.

A few pF is common for connectors with a 0.1 in. pin spacing. The pads add about 0.5 pF on either side of the board-to-board connector.

Circuit Trace Capacitance

If the trace impedance and propagation delay are known, then trace capacitance is given as:

$$C_{\text{per inch}} = \frac{T_d}{Z_0} \text{ pF/in}$$

where T_d is propagation delay in ps/in.

Capacitance of Receivers and Drivers

Receiver cap is usually given in the spec-sheet for the part. If it is not, measure it on a sample using the cap test jig.

Typical values are in the range of 2-10 pF.

The capacitance of a *tri-state driver* when switched to its off state is much **larger** than it is when switched on.

Its value is usually not disclosed by the manufacturer but beware.

Best way to determine *driver* cap is to measure it.

Capacitance of Receivers and Drivers

Power up the driver but leave the outputs disabled.

Bias the pulse generator in the gate's active region and compute the cap. from the response.

Values as high as 80 pF are not unusual!

Very Slow Bus

If speed is not a concern, try src-terminating a multidrop bus.

Here, the tri-state drivers are connected to the bus through a series resistor while receivers connect directly to the bus.

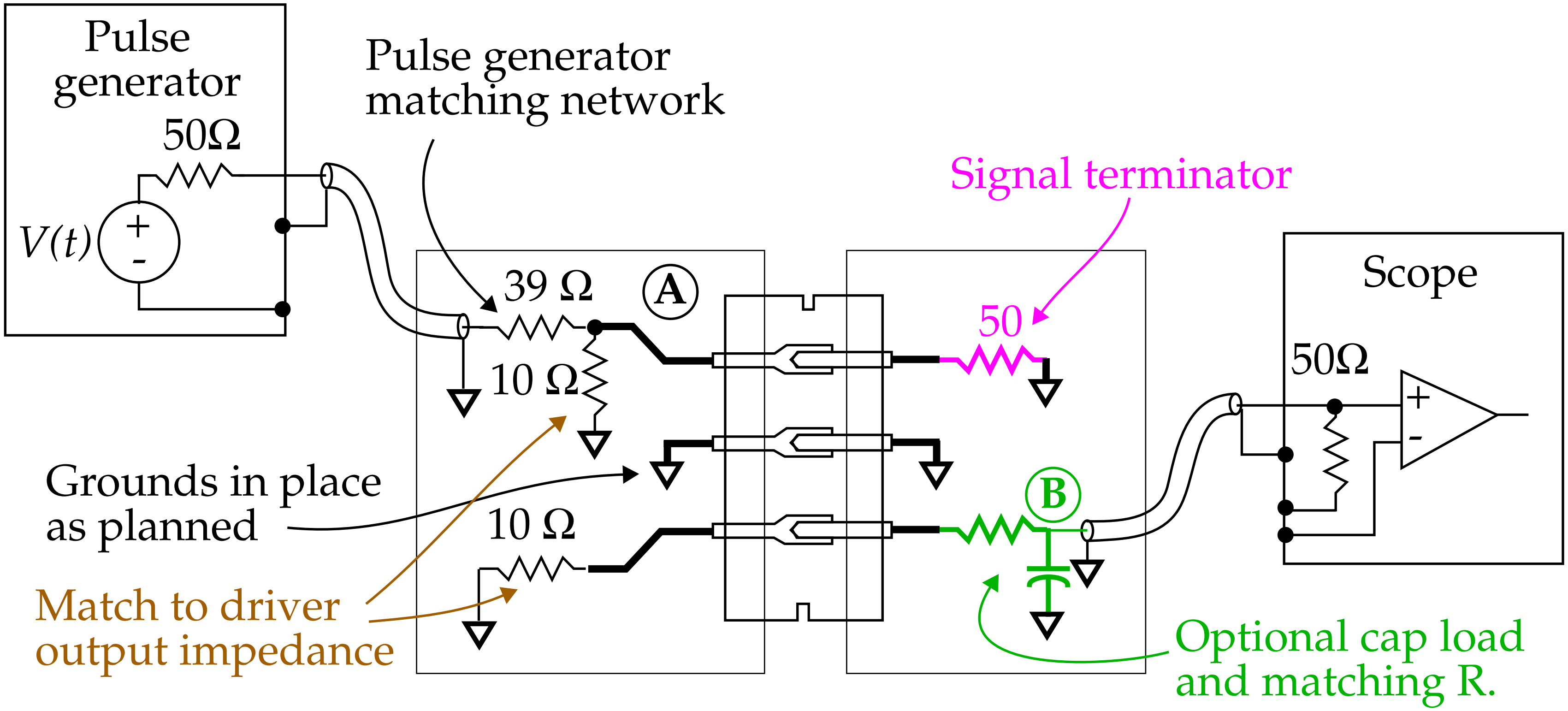
Note that this is **not** the same as our previous src-termination scheme.

The resistors are **not** matched but rather are **much larger**, to slow the rise time such that the bus acts like a lumped RC circuit.

The large R allows the bus to monotonically *leak charge* onto the bus.

Measuring Coupling in a Connector

The following setup measures the performance of any connector under actual operating conditions.



Pulse generator matching network

Signal terminator

Grounds in place as planned

Match to driver output impedance

Optional cap load and matching R.

The pulse generator should be adjusted to produce a signal with a rise time similar to the driver that you'll use.

The scope measures the coupled noise as it will appear in the final circuit.

Measuring Coupling in a Connector

This same configuration can be used for any combination of driven and measured pins to measure coupling at other locations on the connector.

Total crosstalk noise can be computed once other combinations are tested using this setup via superposition.

The matching network on the pulse generator side helps reduce reflections and also provides a *low output impedance* driving the connector.

The 10 Ωs used in the figure should be used if the output impedance of the actual driver is not known.

Set the signal size at point A to the size provided by the actual driver. Scale your results accordingly if this is not possible.

Configure the *signal termination* according to the system you are using, i.e., use a cap if the signal terminates into a gate.

Other details given in text.