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Measurements on a high speed arbiter

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Abstract
Measurements on a submicron CMOS arbiter implementation are presented. Using two uncorrelated asynchronous inputs to the arbiter effective time differences between requests of as low as 10^{-18} sec can be obtained. The metastbility time of the arbiter is plotted against input request time difference and is shown to conform to the classical logarithmic relationship. In submicron CMOS, capacitances are sufficiently low to observe discreteness of charge effects, but thermal noise is more than two orders of magnitude larger than the quanta of voltage represented by the charge on an individual electron, and therefore masks these effects.

Keywords
Asynchronous Design, Arbiters, Metastability, Test.

1. Introduction.

Asynchronous arbiters are characterised by the time taken to recover from a metastable state following two requests that occur close in time. There is usually an exponential relationship between the metastability time and the time between requests, so that $\delta t = Ke^{\frac{-t_m}{\tau}}$ where δt is the time between requests, t_m is the metastability time and τ is a time constant associated with the bistable circuit used to perform mutual exclusion.

We aim here to measure the time constant τ for 0.6μ CMOS arbiter samples supplied by Sun Microsystems, Inc. (Sun), and to investigate whether the exponential relationship still holds at values of time difference lower than 10^{-15} s, where the net charge difference between the two capacitances in the bistable circuit may be less than that on a single electron.

2. Principles

The principle of the measurements is as follows: Each input request to an arbiter is sourced from an independent oscillator of similar, but not the same, frequency.
Let us suppose that a request is signalled by a positive edge input. Then because the two request frequencies are not the same, request R_2 will occur at different times relative to R_1 of between $+\frac{T_1}{2}$ and $-\frac{T_1}{2}$ where T_1 is the period of request R_1 and T_2 is the period of request R_2.
Further, since the oscillators are of fixed frequency, when R_2 occurs, the probability of the time between R_1 and R_2 being within $\pm\delta t$ is $\frac{2.\delta t}{T_1}$.

Over any long time, T, there will be $\frac{T}{T_2}$ occurrences of R_2, and therefore the probability of the time between the two requests being δt or less is: $P = 2.\delta t \frac{T}{T_1.T_2}$

Alternatively, the conditions which cause metastability, will probably occur during a time given by: $T = \frac{T_1.T_2}{2.\delta t}$

When a bistable device is put into metastability, the resolution to valid logic levels will take a time given by: $t_m = \tau.\ln\left[\frac{V_h - V_l}{V_m}\right]$ where V_h, and V_l are the high and low logic levels, V_m is the initial deviation from the metastable state, and τ is the time constant of the bistable.

Here we will assume that $V_m = \delta t.\left(\frac{V_h - V_l}{2.\tau}\right)$, and so $t_m = \tau.\ln\left[\frac{2.\tau}{\delta t}\right]$

Counting the number of metastable incidents lasting longer than t_m gives the average value of T, and since $t_m = \tau.\ln\left[\frac{4.T.\tau.}{T_1.T_2}\right]$, we can plot t_m against T to deduce a value for τ This method is well known and has been successfully used to characterise arbiters for at least 25 years [1].

3. Assumptions

There are two assumptions in the discussion above.

1. The currents and voltages are continuous, and the charge is not quantised by being made up of discrete numbers of electrons. If this were the case, we might expect t_m also to have discrete values, since $V_m.C = n.q$ where C is the capacitance associated with the bistable, and q is the charge on an electron, 1.6×10^{-19}.
   If we take the bistable transistors total input capacitance $C = 0.2$ pF, and the channel resistance $R = 5\text{K}\Omega$, than a typical gain of 10, would give $\tau = 0.1$ ns and the levels of voltage difference should be $\frac{q}{C} \cong 10^{-6} V$. In order to charge C by one electron, using 1V and $5\text{K}\Omega$ we would also need a δt of $\sim 10^{-15}$ s. If δt is not infinitely variable, then T will also take up discrete values, so that we might not expect to see values of t_m longer than about 1.1 ns.
2. Thermal noise in the circuit does not affect the metastability time calculation. This is because for every noise contribution that moves the output trajectory further away from the metastable state, there is another that brings it back nearer. The best discussion, and experimental demonstration of this is to be found in [2].

In fact, the thermal noise in an MOS transistor can be calculated from the equivalent channel resistance, R, and the RMS noise is $V_{rmsnoise} = (4.K.B.T.R)^{0.5}$ [3] where K is

Boltzmann's constant, B is the noise bandwidth, and T is temperature. In the bistable this resistance drives the input capacitance, C, of the other transistor, limiting the bandwidth to $\frac{1}{CR}$, so $V_{rmsnoise} = \left(\frac{4.K.T}{C}\right)^{0.5}$. For $C = 0.2$ pF, the noise is 289 μV, two orders of magnitude greater than the discreteness effect due to the charge on an electron, and therefore discreteness is unlikely to be observed until $C \le \frac{q^2}{4.K.T}$, or 0.0000015 pF at room temperature.

4. Tester

To verify these calculations we used two independently powered, 24MHz screened crystal oscillators to drive the R_1, and R_2 inputs of the arbiter samples.
Subnanosecond ECL logic was used to determine when both R_1, and R_2 had gone high giving a signal, R, and when one of the G_1 , and G_2 inputs, goes low in response, G, (metastability is resolved when this signal goes low).
A pulse formed by the difference between the delay of two coaxial cables following R was then gated with the signal indicating metastability, G, to drive a counter.
Thus the number of incidents when metastability lasted longer than a given delay could be measured. Shows the circuit used.

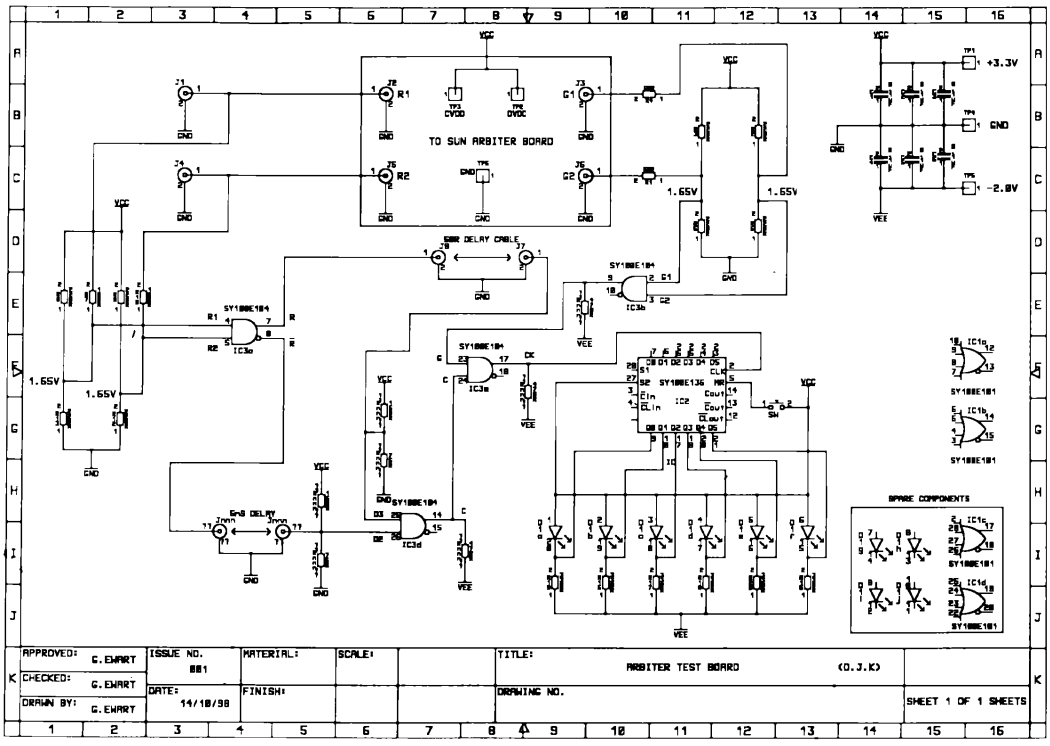

Figure 1 : Tester Circuit

In this circuit the end of the request pulse was determined by one coaxial cable, and kept fixed, and the start time, defined by another, was varied.

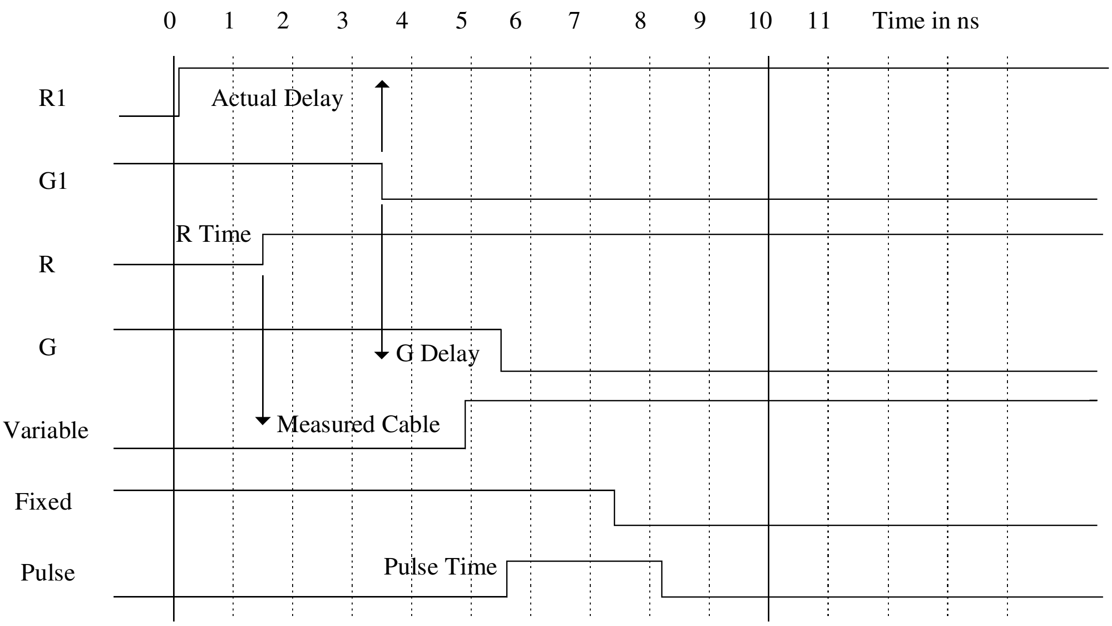

Figure 2: Tester waveforms

The timing of the waveforms in the tester is shown in Figure 2.
In practice, because of the finite response time of the ECL counter we get a count when the G Time overlaps the Pulse Time by about 0.5 – 1 nS, and because of the other gate delays in the paths to the counter, we estimate that the actual metastability time is cable delay + ~1 nS.
Observations of the typical R–G time with no arbitration show about 3 ns delay, probably due to the long input and output pads delays in the sample devices.

5. Results

In our experiment, T_1 and T_2 are each 41.6 ns, and we have taken a series of measurements on the average time between events, T,

Cable delay, ns	2.93	3.03	3.15	3.3	3.48	3.7
T sec	1.57	4.34	17.56	83.07	218	2663
Metastability time ns	3.93	4.03	4.15	4.30	4.48	4.70
Equivalent dt	2.2E–15	7.9E–16	1.9E–16	4.2E–17	1.6E–17	1.3E–18

Converting T into an equivalent value of δt, we have plotted metastability time against equivalent value of δt for our results, and metastability time against actual values published at ASYNC'98 for the same device by Sutherland [4]. For the second set of results, we have assumed a base delay of 3 ns for events where the two requests are widely spaced. These are plotted in , which indicates a value of $\tau = 0.10$ ns for our figures, and a similar value for the Sun figures.

Given the arbitrary nature of the total delay measurement, the two sets of measurements line up remarkably well, and show that classical metastability behavior extends well into the area where individual electrons are involved, because of the subsequent random effects of noise on the trajectory.

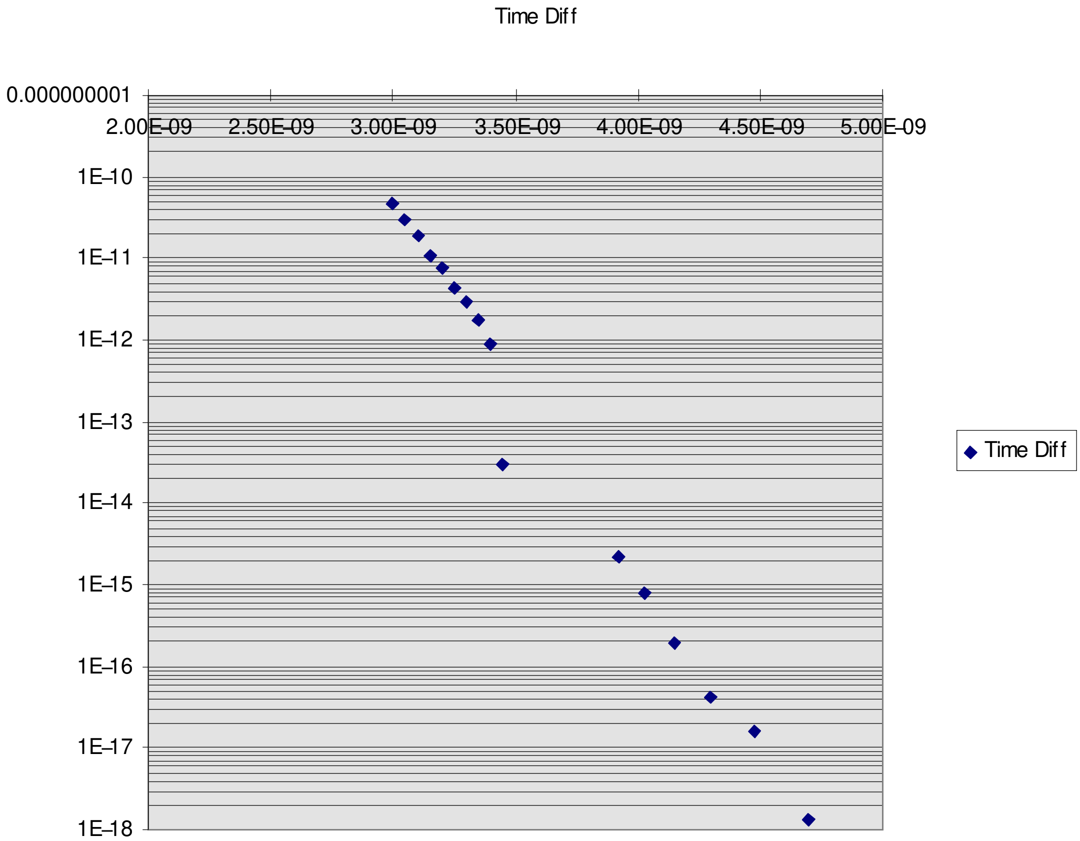

Figure 3: Results

6. Conclusions:

1. The value of τ for the samples supplied is about 0.1 ns.
2. Equivalent time differences of 10^{-18} between requests show no deviations from theory in this technology.
3. The anomalous point in the data presented by Sutherland [4]is probably due to the difficulty of performing the measurement at time differences below 0.1 ps
4. Only if device dimensions could be reduced by more than 5 orders of magnitude, would discreteness of charge become important, or the thermal noise is less than the voltage produced by one electron, for example when 0.005 μ technology is operated at less than 0.2 °K.

7. References

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[3][] Cobbold, R.S.C., “Theory and Applications of Field Effect Transistors” Wiley–Interscience, New York, 1970
[4][ ] Sutherland I, keynote speech, ASYNC’98, San Diego March/April 1998.