Results: In Fig. 2 the imaginary part of the admittance contribution of the separated field is calculated as a function of substrate thickness for the configuration with relative permittivities $\varepsilon_{tr} = 6{\cdot}0$, $10{\cdot}2$, or $13{\cdot}0$, and $\varepsilon_{zr} = 10{\cdot}2$, relative permeability $\mu_r = 1$, $a = 0{\cdot}65$ mm and $b = 2{\cdot}05$ mm (SMA connector), and a' large enough so that $m_t = 0$ at frequencies 1, 10, and 18 GHz (the maximum working frequency of an SMA connector). The real part equals 0. The permittivity values are based on the values for Epsilam-10 material [4]. The effect of uniaxiality and of the relative size of the connector is clearly illustrated.

Conclusion: Using the same line of reasoning as for the case of an isotropic substrate, a coaxial feed located in a uniaxial substrate is studied. Separating a first field distribution, the primary source is transformed into a finite number of voltage sources. The remaining component of the field solution is generated by these sources and has to be determined with a solving procedure for the global structure. The results lead to a highly accurate, partially analytical determination of the input impedance of a structure under consideration.

 29th January 1993

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METHOD FOR AUTOMATED WAVEFORM ANALYSIS OF TRANSIENT RESPONSES IN DIGITAL CIRCUITS

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Indexing terms: Digital circuits, Circuit CAD, Computer-aided analysis

A simple but powerful computer-aided technique is presented for the waveform analysis of transient responses in digital circuits. The technique is targeted towards automatic simulation-based timing and signal integrity analysis and design of digital circuits and interconnects.

Introduction: Simulation-based design, verification and characterisation have been extensively used in analogue, digital and microwave circuit design as well as in interconnect and package design [1]. Any automated simulation-based transient analysis, verification or design procedure requires automatic extraction of certain timing and signal integrity parameters of interest from the waveform representing the response. Examples of such parameters include signal delay, amount of overshoot and undershoot, 'porching', DC level degradation, etc.

Besides extraction of parameters, simulation-based design tools are often required to store or postprocess the waveforms for future use [2, 4]. For example, for comparison with not-yet-obtained waveforms or for constructing an 'eye pattern' [7]. Keeping and handling the integral waveforms requires much memory and effort, especially in large studies consisting of many complex simulation runs. The need for waveform compression arises.

Very often, the designer is interested in comparing only certain features of the waveforms rather than the entire set of features. For example, for macromodel optimisation, the designer might not be interested in only certain signal integrity parameters, e.g. capturing non-monotonicities in the rising edge. In these cases there is no need, whatsoever, to keep the entire waveforms. In contrast, the ability to efficiently extract and independently manipulate different features of waveforms is crucial.

This Letter presents a simple waveform analysis technique which allows for both compact storage, and easy feature extraction and independent manipulation.

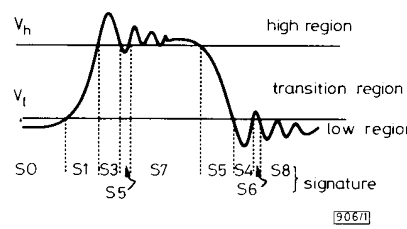

Fig. 1 *Digital waveform and corresponding signature*

Basic method: A transient waveform is represented by a series of points in time–voltage space. For any two arbitrary voltage levels, V_h and V_l, a general waveform can be described in terms of the transitions between successive voltage-time points referenced to V_h and V_l (Fig. 1):

(i) cross high level up: HU

(ii) cross high level down: HD

(iii) cross low level up: LU

(iv) cross low level down: LD

(v) cross successively low and high levels up: LU&HU (i.e. At time step i, the voltage is less than V_l and at time step $(i + 1)$, it is greater than V_h)

(vi) cross successively high and low levels down: HD&LD

(vii) no crosses: N.

The above notion allows the generalised finite state machine of Fig. 2 to be constructed. The constructed machine is a single-input machine with a transition being a six-value input variable (the n transition is omitted). Different states in that

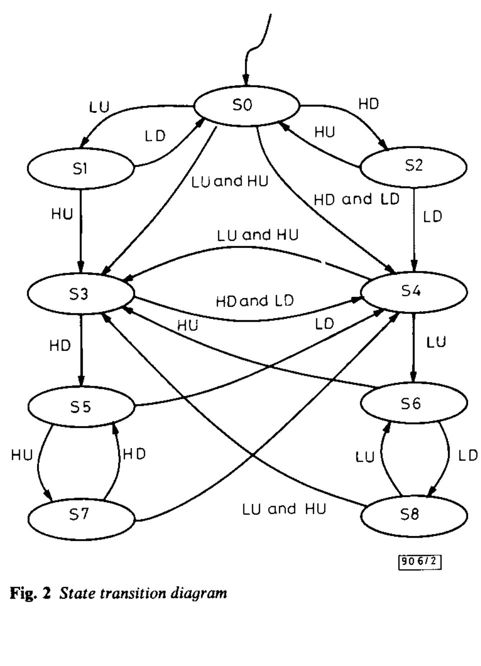

Fig. 2 *State transition diagram*

machine correspond to different regions in the waveform of Fig. 1. This formalism allows every particular waveform to be represented by a corresponding signature, or compressed waveform, defined as a list of all the states the corresponding finite state machine went through for the identified transitions (see Fig. 1 for an example). Relevant timing and voltage information about each state, such as entry and exit times, maximal and minimal voltage values, 'behaviour' while in the state (e.g. monotonic or non-monotonic) etc., are kept in the data structure representing the signature.

The set of states in the finite state machine define a signature alphabet $A_s = \{S0, \ldots, S8\}$. Different events of interest in a waveform such as rising edge, falling edge, undershoot, etc. are now easy to represent by regular expressions [6] over the alphabet A_s. Thus these events can be recognised by pattern matching the expressions with the signatures. The standard regular expressions for some of the events of interest are as follows:

(a) $high\_level = S3 + S7$

(b) $low\_level = S4 + S8$

(c) $transition\_region = S1 + S2 + S5 + S6$

(d) $rise\_edge = [S0(S1 + \lambda) + (S4 + S8)(S6 + \lambda)]S3$

(e) $fall\_edge = [S0(S2 + \lambda) + (S3 + S7)(S5 + \lambda)]S4$

(f) $undsht\_high = (S5S7)(S5S7)^*(S5 + \lambda)S4$

(g) $undsht\_low = (S6S8)(S6S8)^*(S6 + \lambda)S3$

Timing and voltage attributes associated with each identified event are directly extracted from the state-related timing and voltage information stored in the signature.

Obtaining switching, timing and signal integrity parameters: The event timing and voltage attributes are used to determine switching behaviour, timing parameters and signal integrity parameters. Proper 'switching behaviour' at the observed point in the circuit, characterised by the same sequence of logic 0s and logic 1s as the sequence at the excitation point, is checked by simply comparing signatures at these two points. Timing parameters are obtained from the event timing attributes. For example, rise time is the duration of the *rise_edge* event. Signal delay is obtained by comparing timing attributes of corresponding input and output edge events. Signal integrity information is obtained similarly. For example, peak low undershoot is the maximal voltage value during the *undsht_low* event.

The high and low voltage levels, which define the signature of a particular waveform, are set by the user. Multiple levels can be set, if required, resulting in multiple signatures being generated from a single waveform, in a single pass. This is especially useful for analysing signal integrity parameters as functions of different noise budgets [3].

Implementation and application: The above method has been implemented and extensively tested in the waveform analysis module in MetaSim [2, 4], a tool developed for automatic simulation-based characterisation of digital circuits and interconnects.

For the practical case studies we have performed [4], the above method allowed the amount of memory space required for storing the waveforms to be reduced by a factor of 60. Though this case is typical, the average compression ratio varies, depending on the details of the waveform and the reference voltage levels.

One useful application of the above compression technique is the construction of the 'eye diagram' [7], where a large number of waveforms should be kept in memory for graphical reconstruction and superimposing.

Conclusions: By capturing a voltage–time waveform as a sequence of states from a dedicated finite state machine, it is possible to very efficiently store and process the transient response of a digital circuit. By performing pattern matching operations on this summary information, or signature, different signal events can be recognised. Timing and signal integrity (noise) parameters of interest are then extracted using time and voltage information stored within the signature. This extracted information can be applied to problems in automatic circuit verfication, characterisation, optimisation or macromodelling.

Although in our application, the waveforms are obtained from simulation, this technique is also applicable to processing and storing measurement-obtained waveforms.

Acknowledgments: This work was supported by the National Science foundation under grant MIP-901704 and by Cadence Design Systems.

 5th February 1993

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MODIFIED PACKET RESERVATION MULTIPLE ACCESS PROTOCOL

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Indexing terms: Communication protocols, Multiaccess systems

A modified packet reservation multiple access (PRMA) protocol is proposed to minimise premature loss of reservations when the protocol operates in real radio channels where noise and fading errors are prevalent. The proposed protocol is shown to yield significant improvements in performance over PRMA in the presence of channel fading errors.

Introduction: The packet reservation multiple access (PRMA) protocol was proposed by Goodman *et al.* [1] to allow spatially distributed users in cellular systems to transmit packetised voice to a common base station using a shared channel. A reservation protocol is appropriate for packet voice communication because conversational speech produces multipacket messages during talkspurts. PRMA operates with a frame structure which allows each user that has successfully made reservation to transmit exactly one voice packet in each frame.

The performance of PRMA under ideal (i.e. error-free) channel conditions has been studied in References 2 and 3. Because the protocol has been proposed for cellular systems, the extent to which a real radio channel, which suffers from noise and fading errors, impacts on its performance needs to be studied. Channel impairments cause a PRMA user to lose