Conclusion: We have presented a novel low-power and low-voltage D-latch. By using weak pass transistors and a weak inverter, standby power dissipation due to subthreshold current leakage can be eliminated. The circuit is static in nature and can operate down to 1.6V. Although the circuit possesses a higher transistor count, it still performs better in low-power, low-voltage operation.

Acknowledgments: The authors wish to thank M. Ong Geok Pin for his fruitful comments and discussion.

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Electronics Letters Online No: 19980447

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Reduction of bus transitions with partial bus-invert coding

Youngsoo Shin, Soo-Ik Chae and Kiyoung Choi

The authors propose a partial bus-invert coding scheme that reduces the total number of bus transitions further than the conventional bus-invert coding. In the proposed scheme, only a selected subset of the bus lines is considered for the bus-invert coding. Experimental results show that the partial bus-invert coding reduces the number of total bus transitions by an average of 62.4%, compared to that without coding, and by an average of 39.2%, compared to conventional bus-invert coding.

Introduction: Bus transition is a major source of power consumption in bus-based systems. Power consumption for off-chip driving can reach up to 70% of the total chip power, where the bus transition is the most dominant factor [1]; this is because of the large bus capacitances and the large off-chip drivers. Therefore, the reduction of bus switching activity hass a large impact on the reduction of the system power consumption.

The bus-invert code [2] is simple but efficient for data buses, which are generally assumed to be random. The Gray code [3], the T0 code [4], and the Beach code [5] are suitable for instruction address buses because instruction addresses tend to be consecutive. Data addresses are less random than data and less consecutive than instruction addresses. In this Letter, we propose a new bus coding scheme suitable for data address buses, called *partial bus-invert(PBI)* coding, where only a selected subset of bus lines is considered for conventional bus-invert coding. We can select such a subset from among the data address bus lines statically after the algorithm of an application is fixed.

Partial bus-invert coding: In the bus-invert coding [2], if the Hamming distance between the present pattern and the last pattern of the bus exceeds a half of the bus width, the present pattern is transmitted with each bit inverted. An extra bus line, called an *invert* line, is required to send a signal to the receiver side indicating whether or not the bus is inverted. This coding scheme is not always efficient. For example, if there are some bits whose transition probability is very small, it is clearly inefficient to take those bits into account for the bus-invert coding. Furthermore, we have noticed from experiments that the bus-invert coding is not always an optimum solution even when all bits are almost randomly distributed.

In PBI coding, we partition a bus **B** into two subbuses based on the behaviour of patterns transferred. More precisely, for a bus **B** = ($\mathbf{b}^0$, $\mathbf{b}^1$, ..., $\mathbf{b}^{n-1}$), which transfers a sequence of patterns B_i = (b_i^0, b_i^1, ..., b_i^{n-1}), where i is the time index, n is the bus width, and b_i^j is the value of $\mathbf{b}^j$ at time i. We partition **B** into a selected subbus **S** and the remaining subbus **R**, such that **S** contains a group of bus lines having higher transition correlation and higher transition probability, and **R** contains the remaining bus lines. Because the bus lines in **R** have low correlation with those in **S** and low transition activity, they do not need to be involved in the bus-invert coding. Inverting the lines in **R** will rather increase the transition activity than decrease it. Therefore, by applying bus-invert coding for a subbus **S** only, we can reduce the hardware for bus-invert coding as well as increasing its gain. Once **B** is partitioned, the PBI coding is performed as follows. We compute the Hamming distance between S_i', and S_{i+1} where S_i' is the coded version of S_i including the *invert* line; if it is larger than |**S**|/2, set the *invert* line to 1 and invert the lines in S_{i+1} without inverting the lines in R_{i+1}. Otherwise, set *invert* = 0 and let B_{i+1} be uninverted.

One advantage of PBI coding comes from the fact that the bits with less transition probability are not inverted in contrast to bus-invert coding. Another advantage of PBI coding is its lower hardware overhead of encoding and decoding logic, which implies less power consumption. PBI coding becomes bus-invert coding if **S** = **B**. Therefore, the gain of PBI coding is always larger than that of bus-invert coding.

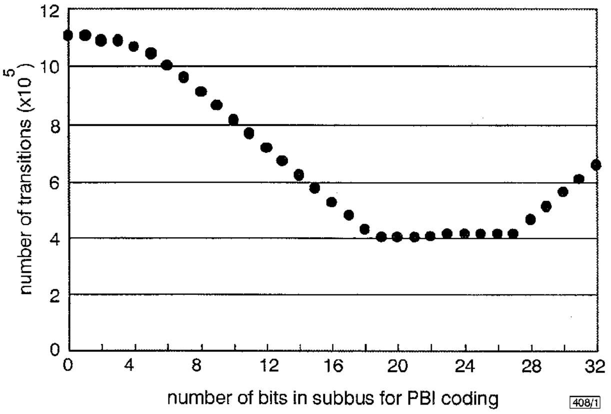

Fig. 1 *Number of total transitions against number of bits coded by PBI coding for lowpass filter example*

Selection algorithm of subbus **S**: The performance of PBI coding heavily depends on selection of the subbus **S** for bus-invert coding. Unfortunately, it is intractable ($O(2^n)$) to find an optimum set $\mathbf{S}_{opt} \subset \mathbf{B}$ such that PBI coding for $\mathbf{S}_{opt}$ results in the minimum number of total transitions. Therefore, we propose a heuristic algorithm that exploits spatial correlation of transitions. Forthe jth bus line, the transition encoding is defined as

$$t_i^j = \begin{cases} 1 & \text{if } b_{i-1}^j \neq b_i^j \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

The correlation coefficient between two bus lines (jth and kth) is defined by

$$\rho_{jk} = \frac{E\{t^j t^k\} - m_j m_k}{\sigma_j \sigma_k} \qquad (2)$$

where $E\{x\}$ is the expected value of x and m_j and σ_j are the mean and the standard deviation of t^j, respectively. The selection algorithm is as follows:

```
$\mathbf{R} = \{\mathbf{b}^0, \mathbf{b}^1, ..., \mathbf{b}^{n-1}\}$, $\mathbf{S} = \{\ \}$; /* Initialise the selected set */
Select $\mathbf{b}^i$ with the highest transition probability;
Store the configuration with $\mathbf{R} = \mathbf{R} - \{\mathbf{b}^i\}$, $\mathbf{S} = \{\mathbf{b}^i\}$;
WHILE ( $\mathbf{R} \neq \{\ \}$ ) DO
        Select $\mathbf{b}^j$ in such a way that $\Sigma_{k \in S}\rho_{jk}$ is the maximum;
        Store the configuration with $\mathbf{R} = \mathbf{R} - \{\mathbf{b}^j\}$, $\mathbf{S} = \mathbf{S} \cup \{\mathbf{b}^j\}$;
END DO
Count the number of total transitions after the PBI coding for each configuration;
Select the configuration that yields the minimum number of total transitions;
```

Fig. 1 shows the result obtained by the above algorithm for data address patterns used in a lowpass filter [6]. Note that in

Fig. 1, the rightmost and leftmost data points correspond to the patterns coded by the bus-invert method and the uncoded patterns, respectively.

Experimental results: We have experimented with several benchmark programs [6] that are usually implemented with ASICs and memory. For each program, we first extracted the data address patterns of memory accesses for a typical run. Then we obtained the results after running the proposed algorithm. We compared the performance of bus-invert coding and PBI coding with respect to the number of total transitions as summarised in Table 1. We do not consider other coding methods such as the Gray code and the T0 code, because they are not suitable for data addresses. PBI coding provides a 62.4% improvement, on average, and up to 71.7% improvement compared to uncoded patterns. It also gives a 39.2% improvement, on average, over bus-invert coding. The improvement obtained with PBI coding is also illustrated in Fig. 1.

Table 1: Comparison of number of total transitions

Applications	Uncoded number of transitions	Bus-invert coding		PBI coding	
		Number of transitions	Reduction	Number of transitions	Reduction
			%		%
Compress	1756468	1066266	39.3	722260	58.9
Laplace	3928218	2377233	39.5	1603476	59.2
Linear	3948001	2420801	38.7	1269001	67.9
Lowpass	1101927	656119	40.5	399702	63.7
SOR	2874978	1900735	33.9	1358804	52.7
Wavelet	2197	1394	36.6	622	71.7
Average			38.1		62.4

The actual gain of PBI coding over bus-invert coding is larger, if we take into account the internal transitions of the encoding/decoding hardware.

Conclusion: In this Letter, we propose a new bus coding scheme, which reduces the number of bus transitions for low power applications. The coding scheme is particularly suitable for memory-intensive special-purpose applications. However, the scheme is general enough to be used in other types of buses. Experimental results show that the proposed coding scheme is much more efficient than other existing coding schemes.

Acknowledgment: This Letter was supported by NON DIRECTED RESEARCH FUND, Korea Research Foundation, 1997.

13 January 1998
Electronics Letters Online no: 19980424

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Analysis of strip-loaded hard struts using finite element method and asymptotic strip boundary conditions

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A finite element formulation combined with an asymptotic strip boundary condition is used for an analysis of the electromagnetic plane wave scattering from struts loaded with strips periodically displaced along the axial direction. The periodicity of the strips is supposed as being small when compared with the wavelength. The enforcement of this approximate boundary condition reduces the periodic vectorial problem to two coupled scalar finite element problems leading to an efficient numerical code.

Introduction: In antenna systems there are many applications which involve strip grids. Recently, these grids have also been employed to reduce the forward scattering from cylinders such as support struts in reflector antennas [1]. This has been accomplished by loading the strut with metallic strips displaced periodically along its axial direction in order to create an artificially 'hard' surface [2]. The improvement in the reduction of forward scattering has led to the development of some numerical codes which allow the analysis of such structures [3, 4]. These codes, based on expanding the field in terms of cylindrical Floquet harmonics, provide an accurate analysis. However, when the distance between the strips is small compared to the wavelength, it has been proved that appropriate approximate boundary conditions can be applied to study the scattering from strip-loaded circular dielectric cylinders [5].

In this Letter, we show how the asymptotic strip boundary conditions (ASBC) [5], which correspond to a unidirectionally conducting screen in a planar case [6], can easily be introduced into a finite element formulation in order to analyse the plane wave scattering from an infinite cylinder of arbitrary cross-section loaded with strips placed periodically along its axis. In particular, by introducing ASBC, we can reduce the study of a periodic three-dimensional electromagnetic problem to that of two coupled bidimensional problems. This results in a very fast code and in a low dynamic memory requirement.

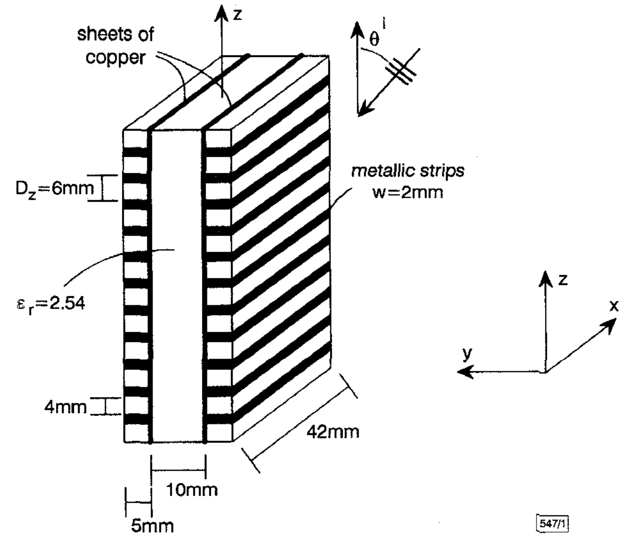

Fig. 1 *Geometry of problem*

Formulation: The geometry of an infinitely long cylinder having its axis parallel to the z-axis of the cylindrical co-ordinate system (ρ, ϕ, z) with period D_z between the strips, is shown in Fig. 1. The direction of the incident plane wave makes an angle θ^i with the positive z-axis and is parallel to the xz-plane. An harmonic time dependence $\exp(j\omega t)$ is assumed and suppressed.

Owing to the periodicity of the problem, we can limit our observations to a three-dimensional basic period $-D_z/2 \leq z \leq D_z/2$. However, if the period D_z between the strips is much smaller than half the free space wavelength (i.e. $D_z < \lambda_0/2$) we can take into account the nonuniform geometry of the structure in the axial direction by using the following approximate boundary conditions [5]:

$$E_z^{(1)} = E_z^{(2)} \qquad E_\tau^{(1)} = E_\tau^{(2)} = 0 \qquad (1)$$