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Reliability bounds for two dimensional consecutive systems

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ABSTRACT

In this paper we consider consecutive systems due to their potential for novel nano-architectures in general, where schemes able to significantly enhance reliability at low redundancy costs are expected to make a difference. Additionally, nanoscale communications are also expected to rely on structures and methods allowing to achieve better/lower transmission bit error rates. In particular, certain nano-technologies, like, *e.g.*, nano-magnetic ones (but also nano-fluidic, molecular and even FinFETs), could be mapped onto consecutive systems, a well-established redundancy scheme. That is why this paper will start by briefly mentioning previous results for one dimensional linear consecutive-k-out-of-n: F systems with statistically independent components having the same failure probability q (i.i.d. components), before focusing on 2-dimensional consecutive systems. We shall introduce 2-dimensional consecutive systems and mention some variations, before going over a few upper and lower bounds for estimating their reliability. Afterwards, we shall present simulation results for particular 2-dimensional cases. These will show that some of the lower and upper bounds are able to perfectly match the exact reliability of 2-dimensional consecutive systems for the particular cases considered here. Conclusions and future directions of research are ending the paper.

1. Introduction

The International Technology Roadmap for Semiconductors (ITRS) report [30] predicts that the semiconductor industry will still continue downscaling CMOS. Big questions waiting for answers are: (1) for how many generations more, and (2) what will follow beyond CMOS. This is because many fundamental and technical challenges must be resolved to continue scaling CMOS, besides very serious economic and financial concerns. The three greatest challenges identified by ITRS are *power* (and the associated heat dissipation), *reliability*, and the overall *complexity* (of fabrication, design, test, etc.). A most worrying aspect is that these challenges are intricately intertwined.

The global picture is that while power is very well appreciated since about a decade, reliability looks like the most daunting threat to the design of future integrated circuits. For novel nano-devices and their associated interconnects, the probabilities of failures are expected to be even higher, as will be their sensitivities to noise and variations. These could make future chips prohibitively unreliable, and also means that the current IC design approach, which is based on the conventional zero-defect foundation, will not work anymore. Therefore, fault- and defect-tolerance techniques (allowing a system to recover

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from faults and errors) should become the norm, being taken into consideration from the very early design phases. That is why, it is to be expected that, since manufacturing processes will not be able to produce perfect nano-devices at reasonable/acceptable costs, future designs will have to be defect- and fault-tolerant, reconfigurable, functioning despite imperfections, and able to diagnose and repair their own failures dynamically. Any future nano-architecture that will disregard the fact that the underneath nano-devices and associated interconnects are unreliable will, most certainly, be impractical.

The classical approach for developing architectures able to tolerate faults (both permanent and transient ones) is to incorporate redundancy in some form. Redundancy can be either static (in space, time, or information) or dynamic (fault detection, location, containment, and recovery). Space (hardware) redundancy includes among others the very well-known modular redundancy, cascaded modular redundancy, and multiplexing [47], but also the less explored hammock networks [39] and interwoven logic [42]. Such space redundancy schemes can be implemented at different levels: device, gate, circuit, block, or system. What they have in common is that enhanced reliability is always traded off for larger area and higher connectivity (which should, at least at first sight, lead to higher power consumptions and slower computations).

A space redundancy scheme, which has received a lot of attention over the last three decades, is represented by various consecutive systems. Examples for the simplest, *i.e.*, one dimensional linear consecutive systems, include: telecommunication systems having n relay stations (*e.g.*, either satellites or ground stations), microwave broadcasting systems, oil pipeline systems (with n pumping stations), belt conveyors (with n rolling stations, like the ones used in the mining industry), vacuum systems in accelerators, and even rows of street lights. These can be approximated as one dimensional linear consecutive-k-out-of-n:F systems having n identical and statistically independent components, with all components having a constant probability of failure q (i.i.d. components).

Another system is represented by neurons, for which the classical explanation for communications is based on local ionic currents [26]. Some explaination is still needed on how the brain takes advantage of pressure waves, temperature and concentration gradients to allow the renewal of the extra-cellular fluid, as well as some forms of intercellular communications at an energy cost way lower than the well-established synaptic transmission [1]. One alternative discusses solitons in the context of mechanical dislocations and temperature changes [25,23,24], while others suggested an axoplasmic pressure pulses [43,4], or electromagnetic pulses [49]. In fact, many studies have shown that a mechanical displacement of the axonal membrane accompanies the electrical pulse which has been used to define an action potential, but there is little theoretical consensus for the physical basis of such waves or their links with the electrical pulse. Very recently [16], a model for the mechanical displacements in which the elasticity of the membrane and cytoskeleton stores the potential energy, while the axoplasmic fluid caries the kinetic energy was put forward. Irrespective of such details, a biological communication system which could be approximated as a one dimensional linear consecutive-k-out-of-n:F system is represented by myelinated axons, where the nodes of Ranvier could be seen as the pumping stations (two major difficulties here being that k depends on the details just mentioned above, and that estimating q for a node of Ranvier is far from trivial).

Many variations of the one dimensional linear consecutive-k-out-of-n:F system have been introduced over the years [6,21,54,32,52,12,53], while the interested reader should consult a review [9] and a book on this topic [7]. The variations include circular, k-within, 2-dimensional (on rectangular or triangular lattices), cylindrical, X-connected (representing a failing pattern), and even 3- and d-dimensional ones. Representative examples here consist of computer networks, alarm/surveillance systems, pattern detection systems, radar detection systems, quality control (LCD displays), acceptance sampling, and DNA sequencing. Based on the results reported in [48] it looks like 2-dimensional consecutive systems should also be a very good model for unmyelinated axons, while [15] shows that they should be considered even for dendrites and nodes of Ranvier. There is also a wealth of articles presenting closed-form formulas for particular cases, limit formulas, algorithms (both recursive and direct), and lower and upper bounds. The methods used to establish these span from combinatorics, through probability theory and switching algebra, to graph theory and others.

Additionally, such consecutive systems could make a large impact on certain nano-architectures as they can enhance reliability significantly at amazingly low costs (*i.e.*, very low redundancy factors). In fact, they seem to be a very good fit for novel nano-architectures in general (where reliability is of high interest), and for nano-technologies allowing for beyond near-neighbor communications in particular (where the reliability of transmissions should also be enhanced). Examples of nano-technologies allowing for beyond near-neighbor communications include magnetic, fluidic, and molecular ones, *e.g.*, implementing quantum-dot cellular automata (QCA) [35] when the radius of induced effect (influence) is larger than the distance between adjacent cells.

This paper will start by briefly reviewing previous results obtained for one dimensional linear consecutive systems [5,13], while mentioning 2-dimensional variations in Section 2. Lower and upper bounds for 2-dimensional consecutive systems will be presented in Section 3. In Section 4, a particular 2-dimensional consecutive-k-out-of-n:F system (for which a closed-form solution is known) will be used to benchmark the accuracy of the different lower and upper bounds presented in Section 3. These will be followed by conclusions and further directions of research.

2. History and variations

A linear consecutive-k-out-of-n:F system, is a one dimensional consecutive system having n components placed sequentially (*i.e.*, in a row), which fails if and only if at least k consecutive components fail. The components are considered statistically independent and having the same failure probability q (i.i.d. components). This concept was introduced by Kontoleon in 1980 [31] and it has been

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