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Reconfigurable Fault-Tolerant Multielectrode Array for Dependable Monitoring of the Human Brain

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***Abstract*— We introduce a fault-tolerant strategy to improve the dependability of a multi-electrode array (MEA), an issue of considerable concern. We propose an interstitial redundancy approach with local reconfiguration. Here spare modules are placed at interstitial sites and can replace neighboring primary modules when they develop faults. We evaluate the performance of such a system under different faults to characterize MEA dependability as a function of redundancy. The results demonstrate that a considerable improvement in MEA dependability can be achieved with a well designed increase in redundancy.**

***Index Terms*— Fault-tolerance, dependability, reliability, availability, intracranial electrodes, intracranial electroencephalogram (icEEG), electrocorticogram (ECoG), implantable medical device (IMD), brain implantable devices, multi-electrode array**

I. INTRODUCTION

In recent years brain implantable devices have emerged as a new approach for the treatment of medically intractable epilepsy [1], one of the most common neurological disorders affecting between 0.4% to 1% of the world's population [15]. Successful treatment is possible pharmacologically for approximately 64% of this patient population [10], and some of the remaining approximately 10-20 million patients who suffer uncontrolled seizures are candidates for brain surgery [4]. Considerable progress has been made in the past two decades through the development, testing and deployment of passive and active neural recording systems for acute, prolonged and permanent use [3], [8], [16]. Some of these systems use silicon micromachined electrodes and most use wires for signal and power transmission. Recognizing the limits of passive devices active devices have also been proposed and developed. Currently brain implantable devices employ electrical stimulation to control seizures [7], [6], [12]. Other implantable devices under development seek to warn of an impending seizure, deliver drugs locally or cool the brain to control seizures.

A brain implantable device for the control of seizures may require permanent monitoring of brain activity to detect or predict a seizure. While currently, a small number of sensors are used, there is mounting evidence that the sensing solution in epilepsy will involve increasingly larger numbers of electrode contacts placed in a dense arrangement, that is, as a multielectrode array (MEA), to cover parts of the cortex which are suspected of involvement in seizure initiation. Such a device is not dissimilar to that used for a brain computer interface (BCI) and for studies of the brain, and the strategy proposed here can be readily extended to the development of a dependable MEAs for those applications. Recently, MEAs with 252 electrode contacts have been designed and manufactured [14] and there are strong indications that MEAs with 1,024 electrode contacts will be available in the near future [2]. The currently available as well as proposed solutions for continuous real-time monitoring of the electrical activity of the brain are all intolerant to faults [11]. Faults which affect sensing can arise due to manufacturing defects, mechanical stress on the sensors or the connecting wires during surgery, gliosis, or from other changes in the brain and surrounding milieu. In extreme cases the development of faults can require a second surgery to replace the malfunctioning device with a new device.

We believe that the reliable sensing of the human brain for an extended period of time necessitates fault-tolerant design to assure system reliability. Here, we consider fault tolerant approaches for intermittent and permanent faults. Transient faults typically do not require system reconfiguration and thus are not considered here. This report focuses on interstitial redundancy, the reconfiguration strategy to recover from detected faults, and the reliability evaluation of this dependable system.

II. FAULT-TOLERANT MULTIELECTRODE ARRAY

The goal of fault-tolerance is to improve system dependability which is defined as the ability of a system to deliver service at an acceptable level of confidence. Of all the attributes of dependability, reliability and availability are the two which are most commonly used to characterize it [9]. The architecture of the implantable device considered here consists of a MEA with multiple contacts (sensors) and electronics to condition and digitize the sensed signals. Each sensor in the sensor array is connected, through a switching network, to signal conditioning and digitizing circuitry which includes an amplifier, one or more filters, an A/D converter and a D/A converter, if one is needed. We assume a modular design where a sensor and its associated signal conditioning and digitizing circuitry is defined as a *module*. We present a fault-tolerant approach based on hardware redundancy wherein we seek to detect and isolate a faulty module and then reconfigure the MEA after isolating and replacing the faulty module with a healthy spare module.

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We propose incorporating spare modules within the MEA design based on a defined geometry. We assume a (*m, n*) array structure shown in Fig. 1(a), where *m* is the number of rows and *n* is the number of columns of the primary (gray) modules. A module is either primary (gray) or spare (black). The spare modules are placed at interstitial sites within the (*m, n*) array of primary modules. Such fault-tolerant structures are represented as an (*s, p*) *interstitial redundancy array* (IRA). In an IRA, each non-boundary primary module can be replaced by one of the *s* neighboring spare modules and each non-boundary spare module can serve as a spare for its *p* neighboring primary modules.

IRAs can have different degrees of redundancy depending on the number and location of spare modules. IRA redundancy is measured by the redundancy ratio , which is the ratio of the number of spare modules to the number of primary modules. For example, consider the (4, 4) IRA shown in Fig. 1(a), where each non-boundary primary module can be replaced by any one of the four spare modules adjacent to it, and each spare module is available to its four neighboring primary modules. The redundancy ratio of this IRA is 1. Furthermore, in this IRA each of the four corner primary modules can be replaced by one spare module and the remaining boundary modules can be replaced by one of the two spare modules. The relationship between primary and spare modules can be described by the graph model for this IRA shown in Fig. 1(b). A node in the graph model represents a module in the corresponding array structure shown in Fig. 1(a). If a spare node can replace a primary node, then in the graph model there is an edge connecting the two nodes. It can be observed that no two gray nodes are neighbors since a primary module cannot replace another primary module. When a faulty primary module is identified a reconfiguration process is initiated to replace it with a fault-free spare module. The fault-tolerant method can be designed with cold spare modules, where a spare module is switched on only if it is brought online during the reconfiguration process. Cold spare reconfiguration helps conserve power and facilitate thermal management of the implantable device.

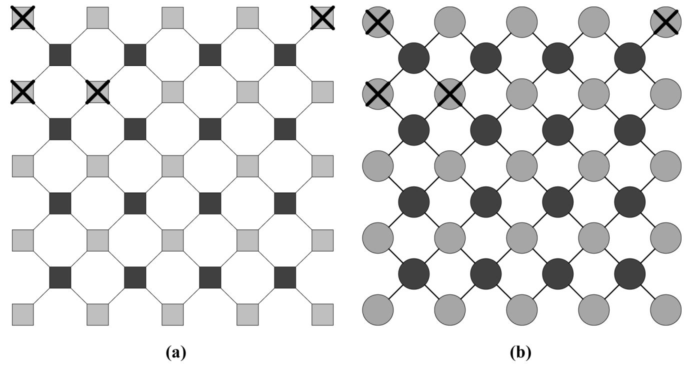

Fig. 1. (a) A (4, 4) interstitial redundancy array (IRA) design with spare module (black) at the interstitial sites of the primary modules (gray), (b) The corresponding graph model where each node in the graph represents a module in the array, with gray nodes representing primary modules and black nodes representing spare modules. An example set of faults is shown in (a) and (b) where primary modules (1, 1), (2, 1), (2, 2) and (1, 5) are faulty, and can be replaced by spare modules (1', 1'), (1', 2'), (2', 1'), (2', 2') and (1', 4'). Here an X marks a faulty module.

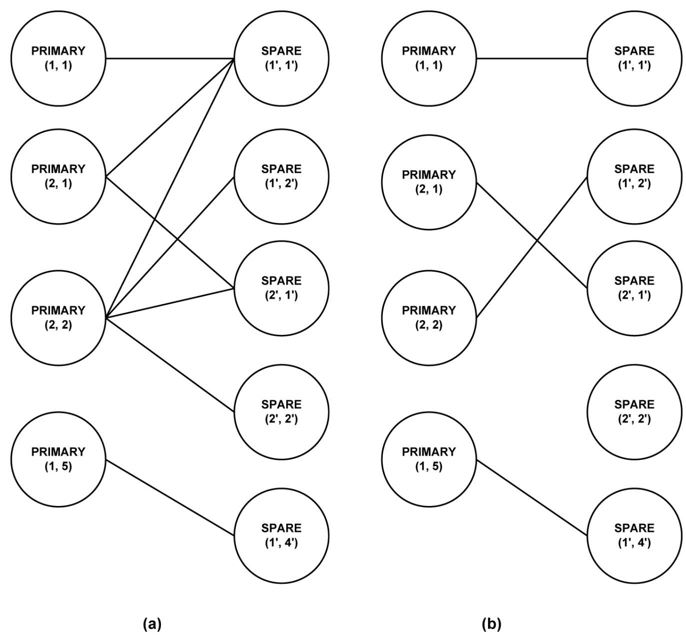

Fig. 2. (a) A subgraph of the four faulty modules shown in Fig. 2(a), and the spare modules which can replace them. (b) A maximum matching of the bipartite graph in 2(a).

III. Reconfiguration and Reliability Analysis of Interstitial Redundancy Arrays

Interstitial redundancy uses local reconfiguration to simplify the reconfiguration strategy. This approach is based on a graph matching approach. The allocation of a spare module to replace a faulty primary module can be performed in an optimum manner by employing a maximum matching algorithm [5]. For example, consider the (4, 4) IRA and its graph model shown in Fig. 1(a) and Fig. 1(b), respectively. A subgraph consisting of the four faulty primary nodes and the fault-free spare nodes that can potentially replace these faulty nodes can be constructed. An edge connecting a primary node and a fault-free spare node exists if and only if the spare node can replace the primary node. It can be observed that this graph is a *bipartite* graph since no two primary nodes or no two spare nodes are adjacent as shown in Fig. 2(a). Any algorithm for maximum flow can be applied to the directed bipartite graph to determine the maximum matching [13] shown in Fig. 2(b). This algorithm can either run on an implanted processor, for example embedded on the MEA, or on a stand-alone computer that communicates with the implanted system.

To evaluate the reliability of a system it is assumed that the system is operating in the useful life phase of the bathtub curve [9]. Thus, the failure rate is considered to be a constant value, λ. Under this assumption it can be shown that the reliability $R_m(t)$ of each module is given by (1):

$$R_m(t) = e^{-\lambda t} \tag{1}$$

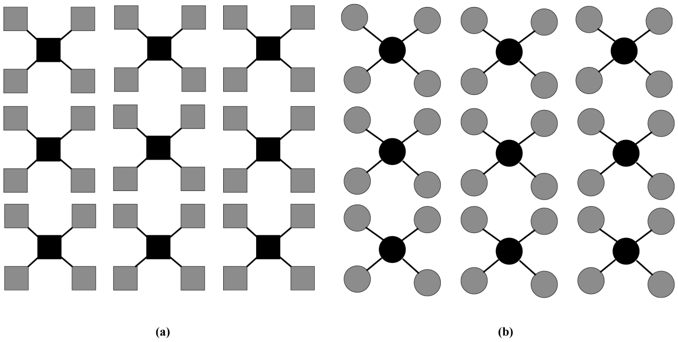

Fig. 3. (a) An example of a (1, 4) IRA with spare modules (black) at the interstitial sites of the primary modules (gray), and (b) the corresponding graph model. Compare this to the example (4, 4) IRA shown in Fig. 1.

For simplicity, failure rates of primary and spare modules are assumed to be equal.

Consider, for example, the (1, 4) IRA shown in Fig. 3(a). In a (1, 4) IRA each primary module has a single spare module, while each spare module can serve as a spare for four primary modules. The redundancy ratio of a (1, 4) IRA is 0.25. Let such a (1, 4) IRA have N primary modules and an array size of m x n where m and n are even numbers. Thus, the MEA has $mn/4$ or $N/4$ identical clusters. Each cluster consists of four primary modules and one spare module. The reliability of each cluster is the likelihood of having at most one failed module among the five modules in the cluster. With the above analysis we can conclude that the reliability of the (1, 4) IRA system with N modules is given by (2):

$$R_{(1,4)}(t) = (R_m^5(t) + 5R_m^4(t)(1 - R_m(t)))^{N/4} \quad (2)$$

Similarly, the reliability of a (1, 6) IRA can be represented by (3):

$$R_{(1,6)}(t) = (R_m^7(t) + 7R_m^6(t)(1 - R_m(t)))^{N/6} \quad (3)$$

The reliability analysis of a (4, 4) IRA system, such as the one shown in Fig. 1, is complex. However, we can find an approximate solution by considering primary modules to be associated with one, two, or four spare modules.

Fig. 4 shows the effect of module reliability on MEA reliability of (1, 6), (1, 4) and (4, 4) IRA MEAs for different values of N and with a fault coverage C equal to 1. Here *fault coverage* is defined as the probability that the system will successfully recover from faults and maintain an operational state. It can be concluded that a design with a greater amount of redundancy, such as a (4, 4) IRA, should be used when module reliability is low while a design with lower amount of redundancy can be used when module reliability is high. We

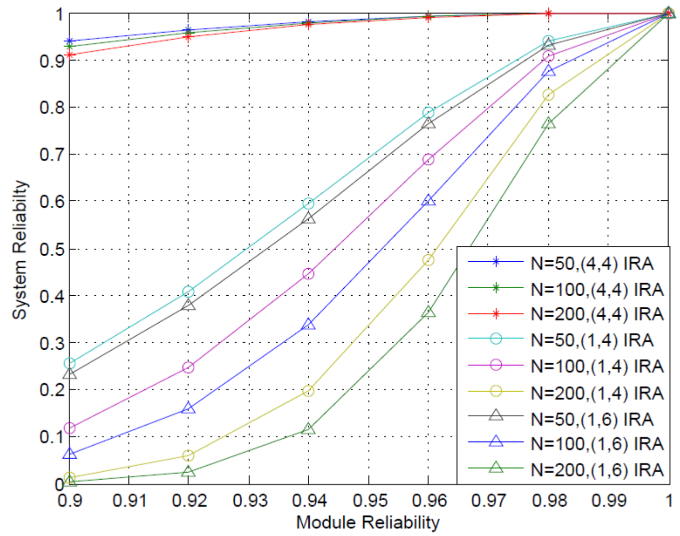

Fig. 4. System reliability of (1, 6), (1, 4), and (4, 4) IRAs with number of primary modules N= 50, 100, and 200 and module reliability $R_m(t)$ ranging from 0.9 to 1.0.

have considered a MEA to be fault-free after reconfiguration if the total number of working modules is equal to the number of primary modules before the occurrence of the fault. A higher value of MEA reliability can also be obtained if a smaller number of working modules suffices to achieve the desired function, that is, if a partial degradation of system function is acceptable.

IV. SIMULATION RESULTS

Of the three IRA structures considered in the previous section, the (4, 4) IRA offered the best system reliability. Therefore, we chose to simulate this configuration to further study its capability for fault reconfiguration. Fig. 5 shows the effect of faulty primary modules on the degree of reconfiguration that is possible in a (4, 4) IRA MEAs with 50, 100, and 200 primary modules. Faults were injected randomly, and simulation was performed to compute the percentage of fault reconfiguration possible. It was observed that all the three IRA structures attained a hundred percent fault reconfiguration when up to 65% of the primary modules were faulty. As the number of random faults increased to seventy-five percent, the (4, 4) IRA with 50 and 100 primary modules resulted in less than perfect reconfiguration. The MEA with 200 primary modules could recover from all the faults till the fault percentage increased to 80%. These MEAs did not have any spare modules on the boundary. The performance can be further improved by incorporating spare modules on the boundary, which in effect, increases the redundancy ratio.

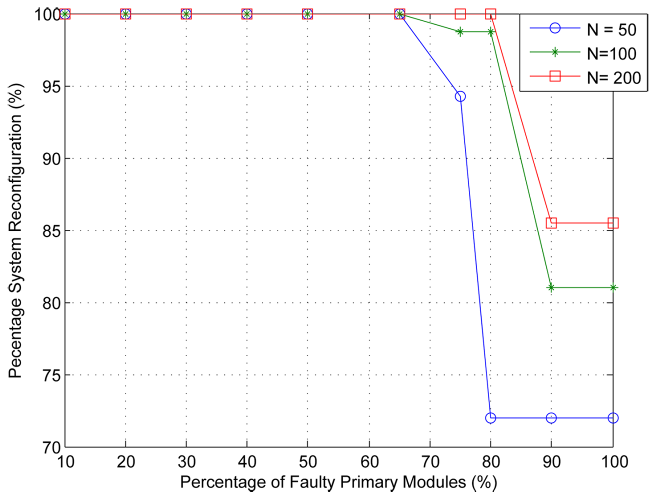

Fig. 5. Fault reconfiguration in a (4, 4) IRA with N = 50, 100 and 200 and percentage of faulty primary modules ranging from 10% to 100%.

V. CONCLUSION

We have introduced an approach to improve the dependability of a MEA. This approach uses space redundancy with local configuration capability where spare modules are placed in the interstitial sites of the MEA and can replace faulty neighboring primary modules. The reconfiguration process to replace faulty modules in interstitial redundancy is simple since it involves only neighboring modules. A considerable increase in system dependability can be achieved with a small increase in redundancy. The concepts presented here can be applied to implantable devices with multiple sensors which are employed for other parts of the body and for other diseases and disorders.

REFERENCES

[1] T. Akin, K. Najafi, and R.M. Bradley. A wireless implantable multichannel digital neural recording system for a micromachined sieve electrode. *IEEE Journal of Solid-state Circuits*, 33:109–118, 1998.
[2] M. Baker. From promising to practical: tools to study networks of neurons. *Nature Methods*, 7(11):877–883, 2010.
[3] J. Csicsvari, D.A. Henze, and B. Jamieson, et al. Massively parallel recording of unit and local field potentials with silicon-based electrodes. *Journal of Neurophysiology*, 90(2):1314–1323, 2003.
[4] J. Engel. Surgical treatment for epilepsy. *JAMA: The Journal of the American Medical Association*, 300(21):2548–2550, 2008.
[5] S. Even. *Graph Algorithms*. Computer Science Press, 1979.
[6] R. Fisher, V. Salanova, and T. Witt, et al. Electrical stimulation of the anterior nucleus of thalamus for treatment of refractory epilepsy. *Epilepsia*, 51(5):899–908, 2010.
[7] R.S. Fisher and A. Handforth. Reassessment: Vagus nerve stimulation for epilepsy. *Neurology*, 53(4):666, 1999.
[8] D.R. Kipke. Implantable neural probe systems for cortical neuroprostheses. In *Proceedings of the 26th Annual International Conference of the IEEE EMBS*, volume 2, pages 5344 –5347, 2004.
[9] I. Koren and C.M. Krishna. *Fault Tolerant Systems*. San Francisco: Morgan Kaufmann, 2007.
[10] P. Kwan and M.J. Brodie. Early identification of refractory epilepsy. *New England Journal of Medicine*, 342(5):314–319, 2000.
[11] B. Lanning, B. Joshi, and T. Kyriakides, et al. Emerging technologies for brain implantable devices. Editors: I. Osorio, H.P. Zaveri, M.G. Frei and S. Arthurs, CRC Press, 2011.
[12] M. Morrell and the RNS System Pivotal Investigators. Results of a multicenter double blind randomized controlled pivotal investigation of the RNS system for treatment of intractable partial epilepsy in adults. *Annual Meeting of the American Epilepsy Society (AES)*, 2009.
[13] C. H. Papadimitriou and K. Steiglitz. *Combinatorial Optimization, Algorithms and Complexity*. Englewood Cliffs, NJ: Prentice-Hall, 1982.
[14] B. Rubehn, C. Bosman, and R. Oostenveld, et al. A MEMS-based flexible multichannel ECoG-electrode array. *Journal of Neural Engineering*, 6(3):109–118, 2009.
[15] J.W.A.S. Sander. ILAE Commission Report The epidemiology of the epilepsies: Future directions. *Epilepsia*, 38(5):614–618, 1997.
[16] D.S. Won, L. Obeid, and J.C. Morizio, et al. A multichannel CMOS analog front end IC for neural recordings. In *Proceedings of the 2nd Joint EMBS/BMES Conf., Engineering in Medicine and Biology*, volume 3, pages 2070 – 2071, 2002.