Self-Healing RF/Microwave Communications Circuits/Systems for NASA Missions—A Review

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Abstract—**The success of current and future NASA missions relies in great part on the performance reliability and robustness of the communication circuits and systems of said missions. Some of the manifestations of reliability and robustness are comprised by properties such as graceful degradation, which provide redundancy and potentially longer life to the mission, and the ability to perform efficiently in harsh environments destinations such as Venus and the Jovian and Saturnian moons Europa and Enceladus, respectively. While several approaches have been considered or are currently underway to develop communications circuitry capable of performing in harsh environments, they lack the flexibility to enable reconfigurability to preserve functionality under adverse or contingency scenarios. This paper discusses some examples of self-healing RF/Microwave communications circuits and systems that could provide advantageous options in support of NASA missions.**

Keywords—self-healing, power amplifier, low noise amplifier, phased array antenna, transceiver, radio-on-a-chip, system-on-a-chip, cognitive, self-adaptive

I. INTRODUCTION

NASA's Artemis program is developing the Space Launch System (SLS), the Orion spacecraft, and a new Human Landing System (HLS) to send astronauts to the surface of the Moon by 2024 [1]. One of the goals of this program is to accomplish outstanding lunar science as outlined by the National Academies [2]. With this vision in mind, NASA's Science Mission Directorate (SMD) is leading the Commercial Lunar Payload Services (CLPS) initiative to encourage U.S. commercial space industry to introduce new lander technologies to deliver NASA and commercial payloads including science instruments and technology demonstrations to the surface of the Moon [3]. In addition, the Artemis program is developing the Gateway to provide a staging point in lunar orbit for long-term sustainable human and robotic surface exploration demonstration missions [4]. At the lunar South Pole, NASA, and its partners plan to develop an Artemis Base Camp to support longer expeditions on the lunar surface. The planned Base Camp elements includes a lunar terrain vehicle (LTV) and new generation of exploration extravehicular mobility unit (xEMU) spacesuits for astronauts while exploring the surface. The above incremental buildup of capability around the Moon is essential for preparing for human exploration of Mars.

Furthermore, the strategic objective of the Planetary Science Division within NASA's SMD is to advance scientific knowledge of the origin and history of the solar system [5]. The scientific foundation for this endeavor is the planetary science decadal survey [6]. The decadal survey besides other investigations prioritizes the study of the inner planets and the giant planets of our solar system. These include Venus and Jupiter and its icy Moons. Venus may be volcanically active. Jupiter's icy moons harbor oceans below their ice shells: conceivably Europa's Ocean could support life. To explore Venus and Europa robotically requires spacecraft with science instruments that can survive extreme hot temperatures, extreme cold temperatures, and high-energy radiation.

To accomplish the above ambitious goals, the Agency plans to work with Artemis providers to ensure spacecraft are built to international interoperability standards with as many reusable components as possible for long-term sustainability at the Moon [1]. Moreover, SMD on occasion has also solicited targeted instrument development efforts as shown in the following examples. First, Concepts for Ocean worlds Life Detection Technology (COLDTech), which supports the development of spacecraft-based instruments and technology for surface and subsurface exploration of ocean worlds such as Europa, Enceladus, and Titan. Second, Instrument Concepts for Europa Exploration-2 (ICEE-2), which supports the development of instruments and sample transfer mechanism(s) for Europa surface exploration. Third, Hot Operating Temperature Technology (HOTTech), which supports the advanced development of technologies for the robotic exploration of high-temperature environments such as the Venus surface.

A simple means to ensure long-term survivability and reliable operation of the robotic spacecraft, landers, rovers, and science instruments at remote locations under the above extreme temperatures and radiation conditions is to add additional shielding. However, the approach of adding shielding adds mass and reverses the benefits of using a smaller and lighter spacecraft and payloads. Typically, from cost considerations a trajectory that consumes minimum amount of propellant by the spacecraft and its launch vehicle is often chosen for interplanetary travel. However, a mission can chose a trajectory that can lower the exposure to radiation and minimizes radiation damage. Choosing a different trajectory may inadvertently increases the mission travel duration and require higher amount of propellant. Furthermore, missions may select hardness-by-design approach to overcome susceptibility to radiation effects. However, this approach may lead to overall device area penalty, increased capacitance, and lower operating speed. In-orbit servicing is another option, which is being considered for satellites in low Earth orbit [7], [8]. However, for deep space planetary exploration the cost may be prohibitive. In the above situations, hardware that is cognitive about impending failures and is capable of autonomously repairing itself or self-healing becomes particularly important.

The 2020 NASA Technology Taxonomy compiled by the Office of the Chief Technologist indicate 17 technology areas that articulate diverse technologies relevant to NASA's missions [9]. The 17 technology areas include self-healing systems, self-healing materials, and self-healing software.

In this paper, we will focus mainly on self-healing systems and present a review of self-healing techniques relevant to several radio frequency (RF) and microwave communication circuits and systems. The cause for the degradation among other factors includes sensitivity of the circuits to variations in the fabrication process, die performance yield, operating voltage/currents/power, ambient temperature, device aging and high energy radiation. Hence, we have listed below techniques that can combine sensing functions achieved through embedded sensors/controlers with self-healing:

(1) Identifying any circuit performance degradation and then modifying or reconfiguring the circuit in real-time to compensate for the degradation.

(2) Designing circuits that are resilient to signal interference. In this case, the design is guided by prior insight into the operation of the system.

(3) Sensing the circuit performance variations and then autonomously reconfiguring or tuning the circuit elements and conducting in-situ calibration to restore performance.

(4) Continuously monitoring and optimizing performance of the system throughout its lifetime and include tunability, to allows for adjusting the system autonomously as the devices age.

In the sections that follow, examples of self-healing RF and microwave circuits and systems that have potential applications in future NASA mission such as those indicated earlier in this section are presented.

II. SELF-HEALING RF AND MICROWAVE CIRCUITS AND SYSTEMS

A. Monolithic Microwave Integrated Circuit (MMIC) Power Amplifiers (PA)

The goal of a Class A microwave PA design is to deliver a maximum linear power with maximum power added efficiency (PAE) and excellent linearity. Circuit analysis indicates that there is an optimum load impedance which satisfies this requirement. A PA with an optimum load impedance is said to be operating under optimum power-matched condition.

In modern active phased array antenna systems, each radiating element is integrated with a solid-state transmit/receive (T/R) module, which has a PA and a low noise amplifier (LNA) [10]. The PA in this setup may experience significant load impedance variations or mismatch due to mutual coupling between array elements as the main beam is steered away from bore sight [11]. The mismatch might degrade the PA performance and eventually lead to PA failure. By integrating a coupler with power detectors or sensors at the output port of the PA all on a single MMIC chip, the forward as well as reverse power flow to the antenna element can be monitored (Fig. 1). If the mutual coupling between elements is small, then the power traveling in the forward direction as input to the array elements is maximum and consequently as desired, the phased array's effective isotropic radiated power (EIRP) is also maximum. On the other hand, if the power flow in the reverse direction increases then either the undesired mutual coupling has increased or the environment surrounding the phased array antenna has changed. Thus, the above sensing capability enables the control circuitry in the phased array system to be cognitive about the PA's operating status and pre-empt a failure from happening. This can be accomplished by integrating a tunable filter, which also serves as a low loss tunable impedance matching network at the output of the PA [12].

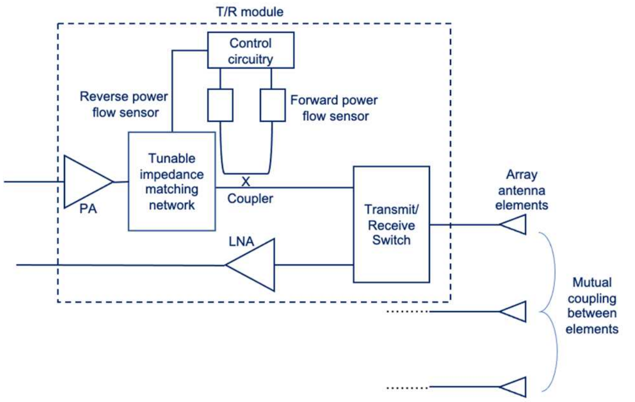

Fig. 1. Schematic illustrating the autonomous reconfiguring of the output power from the phased array T/R module power amplifier (PA) in the presence of mutual coupling.

Additionally, the transmit module in a phased array can be designed to be mutual coupling resilient. This is possible if a balanced configuration with two PAs whose outputs are combined through a quadrature hybrid coupler (QHC) is used for exciting each antenna element [13]. The undesired mutual coupling signal is split by the QHC, reflected from the PA's, and adds at the QHC isolated port where it absorbed by the matched load. However, at the QHC antenna port, the reflected signals cancel each other and provide a perfect match. More discussions on phased array antennas are presented in a separate section below.

B. MMIC Low Noise Amplifier (LNA)

The LNA precedes all other component in a receive module and hence has strict requirements of low noise figure, high associated gain, excellent linearity, excellent input impedance match, and low power consumption. In a typical operational phased array antenna system, the receive modules are placed behind and in proximity with the radiating elements to minimize the interconnection losses that impacts the receiver noise figure (NF). Since the radiating elements are exposed to the environment, the temperature inside the module can fluctuate depending on the conditions outside and could have serious consequences on the LNA noise performance.

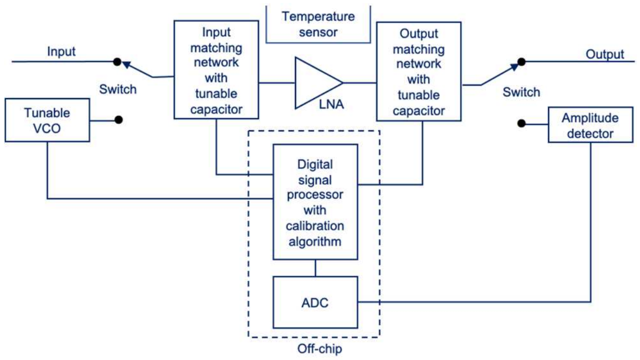

Fig. 2. Schematic illustrating the autonomous reconfiguration/self-healing of the low noise amplifier (LNA) noise figure (NF) and gain as temperature changes.

By designing a LNA that can reconfigure or tune itself autonomously, the degradation in the noise figure (NF) and gain with temperature changes can be recovered (Fig. 2). This is accomplished by integrating on chip tunable capacitors in the input and output matching networks of the LNA, a tunable voltage-controlled oscillator (VCO) at the input of the LNA, and an amplitude detector at the output of the LNA [14]. The recovery process can be autonomous by including off-chip a digital signal processor with a calibration algorithm and an analog-to-digital converter (ADC) that converts the analog output signal from the amplitude detector to a digital signal that adjusts the tunable capacitor values. At the desired operating frequency as determined by the VCO, the tunable capacitor values are adjusted till amplitude detector output is a maximum. At which point, the NF and gain would be restored to its design value under changing operational and environment conditions.

C. Transceiver or Radio-on-a-Chip

Today's CMOS technology can efficiently integrate analog and digital functions on a single chip resulting in a mixed-signal system-on-a-chip (SoC). In the example presented below, the transmitter (Tx) in the transceiver operates in two modes, namely, the QPSK/16 quadrature amplitude modulation (QAM) "data" mode, which is the "normal mode" of operation, and "healing" mode, in which the built-in 10-bit 2GS/s direct digital frequency synthesizer (DFS) generates a single-tone test signal and a two-tone test signal with adjustable frequencies and amplitudes [15], [16]. These signals are used to characterize the Tx using embedded or built-in test and calibration circuits, and in real time self-heal the transmitter impairments. The image rejection ratio or suppression and third-order intermodulation product level (OIP3) at the output of the Tx PA are indicative of the degree of impairments. The causes for these impairments include aging and temperature effects. The first step in the Tx self-healing mode is to measure the image frequency rejection ratio. This is done by applying the single-tone test signal from the DFS to the I and Q channels of the Tx chain and adjusting the amplitude and phase of the Q channel signal in small increments till the image signal is less than -40 dBc. Next, the two-tone test signal is applied to the I and Q channels and this time around, the Tx PA voltage and current are adjusted incrementally to reset the gain till the OIP3 is less than -40 dBc.

The self-healing of the receiver (Rx) is initiated by first measuring the receiver chain path gain. This is done by coupling the two-tone signal from the Tx to the Rx and measuring the tone amplitudes. Next, the Tx is shut down and output noise (N_0) power from the receiver chain is measured. The parameter estimator that contains the fast Fourier transform processor, within the self-healing controller (SHC) does the two-tone amplitude as well as the noise power measurements. Knowing the gain, N_0, Rx bandwidth, and temperature (T) (thermal noise floor = kT, where k is the Boltzmann constant), the noise figure (NF) can be estimated. Based on the estimated NF the SHC adjusts the bias current to the LNA stage to optimize the NF in real time.

In the above example, the SHC occupies an area less than 10% of the entire transceiver as overhead and consumes power less than 3% as overhead based on 2% duty cycle for the self-healing routine [15]. Hence, self-healing circuitry has negligible impact on the overall system size, mass, and power.

D. Phased Array Antenna System

In a phased array antenna, the array elements are excited in various amplitude and phase to generate a desired far-field radiation pattern. The far-field pattern is specified in terms of the antenna half-power beam width, side lobe level, and field of view. If any of the elements in the array were to fail, the far-field radiation pattern would be impacted. A digitally controlled self-healing phased array antenna system with built-in capability to self-diagnose, autocorrect, and reconfigure to mitigate degradation or loss of one or more T/R modules while in active use has been presented in [17]. The role of the self-diagnostic sub-system is to monitor, detect, and diagnose element failures. The autocorrect sub-system administers adjustment to the failed elements to bring its performance within acceptable range. The selection of parameters for adjustment is based on empirical data or acquired using computer models. The reconfigure sub-system adjusts the parameters of the array to compensate for the elements that failed autocorrect. In the reconfigure mode, knowing which elements have failed, an algorithm such as the vector-space projections (VSP) algorithm can be used to reconfigure the array to recover the lost performance [18]. This can be done by adjusting the amplitude and phase settings of the remaining functional elements in the array. As an example, the efficacy of the above VSP algorithm for a 16 x 16 square array with 256 elements is presented in [18]. In this demonstration, 30% or 77 elements were made inoperable and in the reconfigure mode the VSP algorithm was able to restore the performance of the array within the range of acceptable performance, albeit with reduced gain.

It has always been a challenge in a large array, to identify the elements that have failed. Current state of practice accomplishes this task with the help of additional electronics circuits embedded in the array health management systems. However, future phased array antenna systems can include machine learning algorithms such as artificial neural networks and support vector machine (SVM), that can be trained to classify failure scenarios by examining the far-field radiation patterns [19], [20]. Such a system would not only be resilient, but also improve over time by learning from experience and become more useful.

III. CONCLUSIONS

The goals of NASA's Artemis program are highly ambitious and plans to build capabilities around the Moon, which would eventually enable human exploration of Mars. Since the distances involved are enormous robust communications between the spacecraft and Earth are essential for mission success. Hence, autonomous systems based on self-healing can have a significant role. A review of self-healing RF/microwave communications circuits and systems is presented along with examples that demonstrate that they are cognitive and can autonomously tune or reconfigure the circuit/system electrical performance.

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