

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

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Outline

- Introduction
 - Motivation for the effort
 - NASA mission requirements
 - Approaches
- Self-Healing Techniques Relevant to RF/Microwave Space Communications
- Examples of Self-Healing Circuits & Systems
- Conclusions & Discussions

Motivation

- 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
- 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
- Furthermore, 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 payloads to the surface of the Moon
- Moreover, the Planetary Science Division within NASA's SMD plans to use robotic spacecraft and landers to advance scientific knowledge of the origin and history of the solar system

NASA Mission Requirements

- To accomplish these 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
- Additionally, while operating in the harsh environment of space, the Agency is cognizant that the devices and systems for communications and data handling are subject to extreme temperature variations and high energy radiation
- Furthermore, to facilitate the use of smaller spacecraft with lighter payloads and to perform reliably over extended periods, the above devices and systems are required to have small size and low mass, consume small amount of DC power, and operate with high efficiency

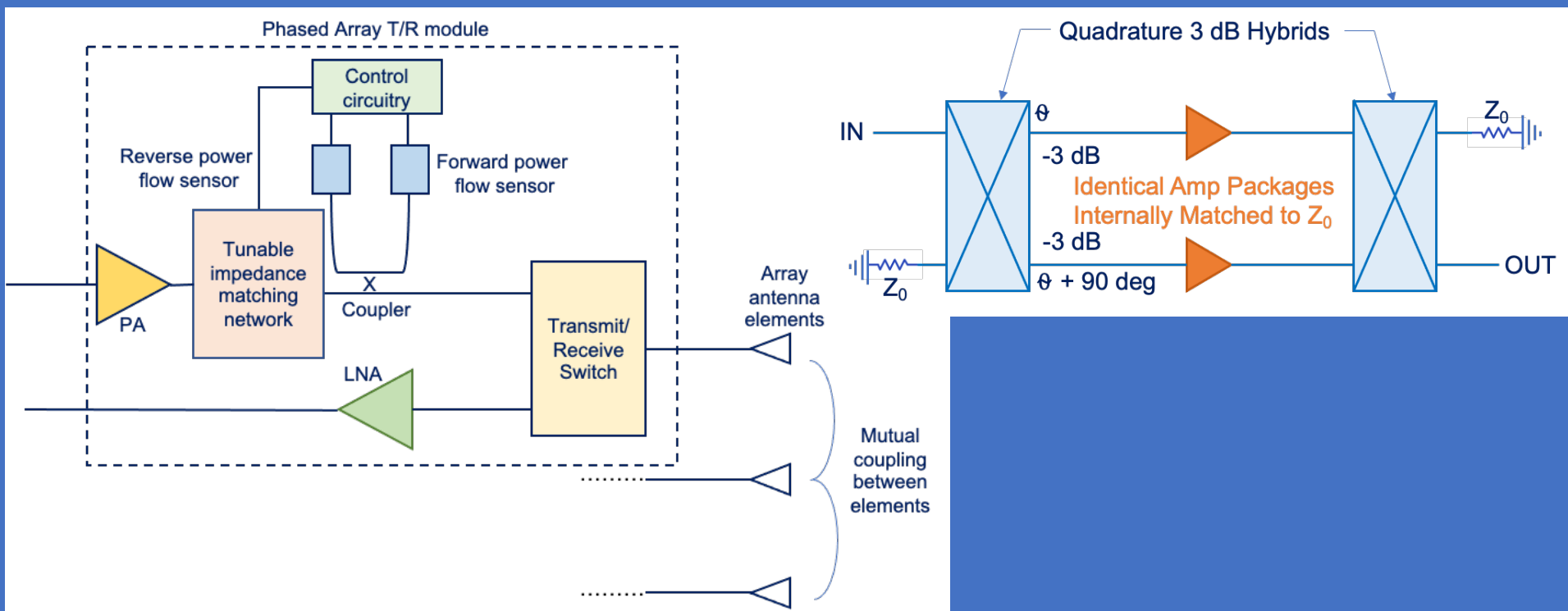
Approaches

- Simple means to ensure long-term survivability and reliable operation of the robotic spacecraft, landers, rovers, and science instruments at remote harsh locations include the following:
 - Add shielding — adds mass & reverses the benefit of smaller and lighter spacecraft and payloads
 - Change trajectory to lower the exposure to radiation and minimize radiation damage — increases the travel time and cost of fuel
 - Select radiation hardness-by-design — leads to device area penalty, higher capacitance, & lower operating speed
 - In-orbit servicing — although recommended for satellites in GEO, it is cost prohibitive for deep space missions
- In the harsh environment of space, hardware that is cognitive about impending failure and is capable of autonomously repairing itself or self-healing is considered favorably

Techniques that Combine Sensing Functions with Self-Healing

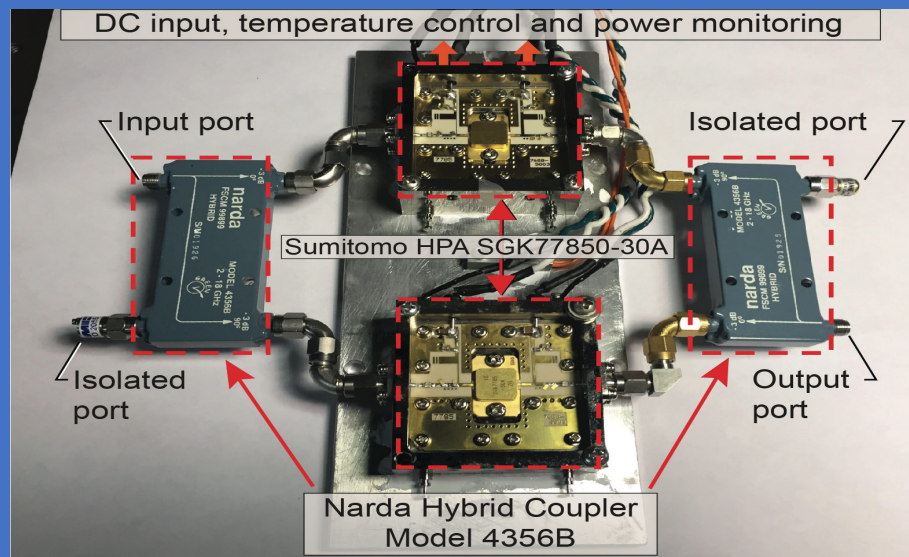
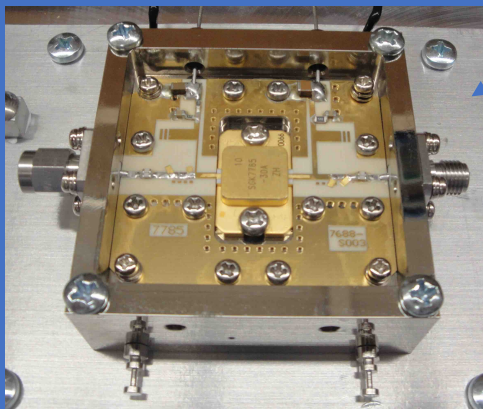
- Identifying any circuit performance degradation and to modify and reconfigure the circuit in real-time to compensate for the degradation
- Designing circuits that are resilient to signal interference
- Sensing the circuit performance variations and then autonomously reconfiguring or tuning the circuit elements and conducting in-situ calibration to restore performance
- Continuously monitoring and optimizing performance of the system throughout its lifetime and include tunability, to allow for adjusting the system autonomously as the devices age

Autonomous Reconfiguring/Self-Healing of Power Amplifier (PA) Output Power

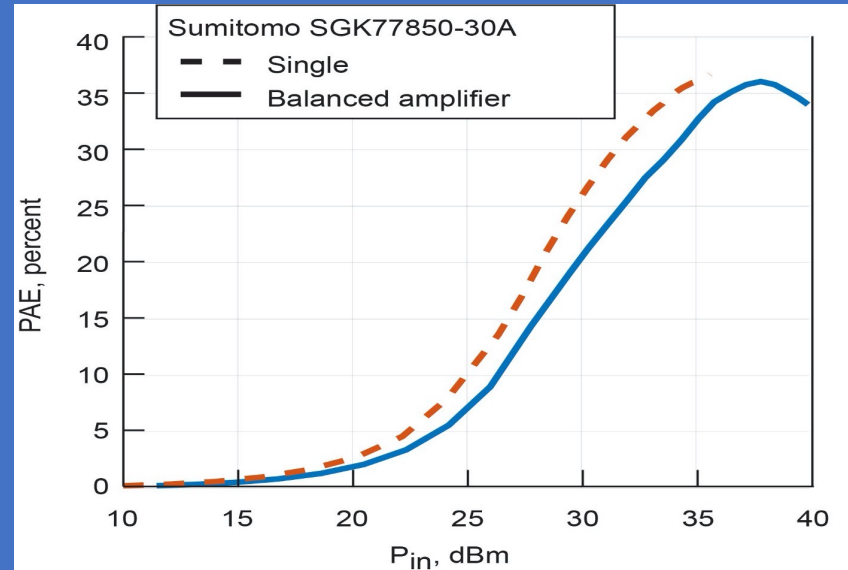
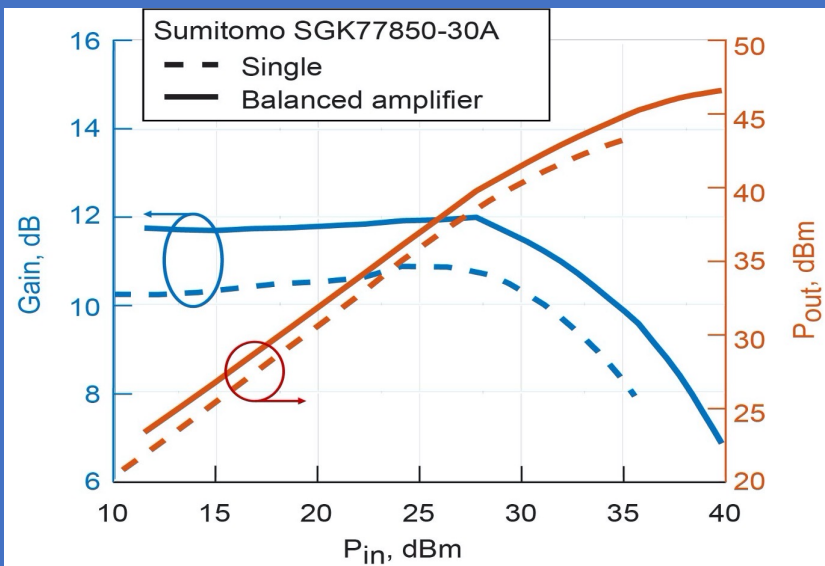


- In a phased array T/R module, the class-A PA operates with optimum load impedance
- As the main beam is steered away from bore sight, mutual coupling between array elements causes significant load impedance variations — PA's performance degrades
- The phased array system being cognitive of the PA's status initiates self-healing
 - Tunable impedance matching network
 - Balanced PA configuration

X-Band GaN Balanced Amplifier Output Power, Gain & Power Added Efficiency

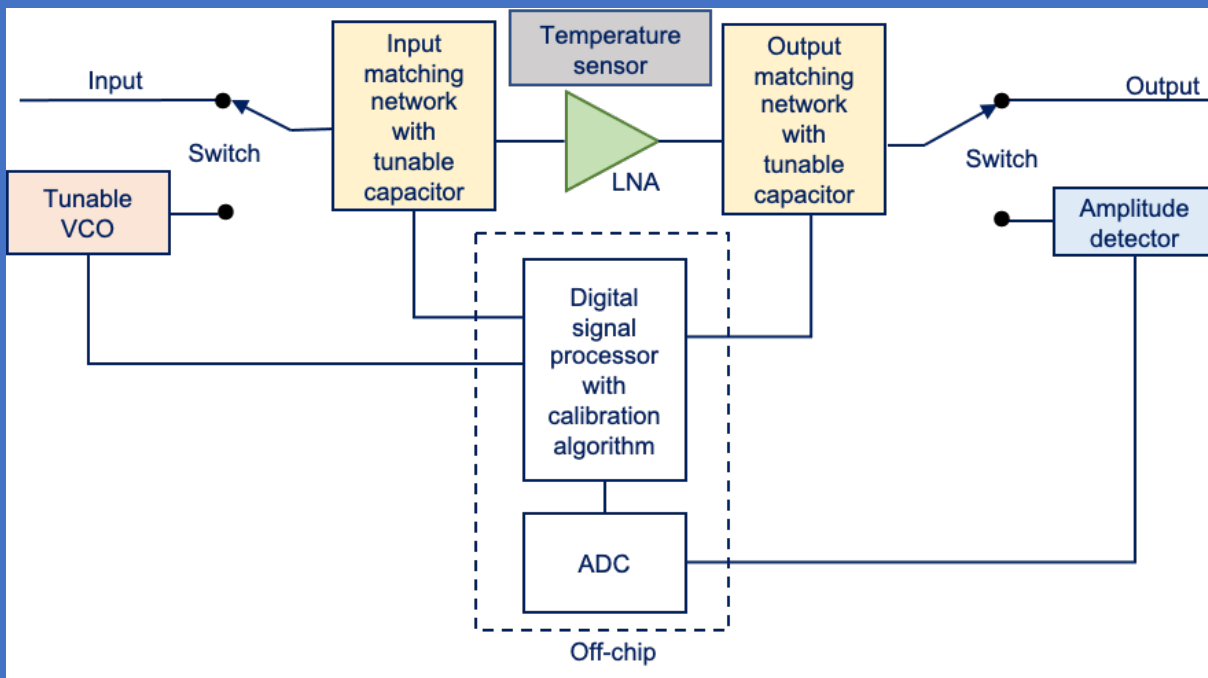


$P_{\text{sat}} = 46.7 \text{ dBm}$ (46.8 watts), PAE = 34%



Autonomous Reconfiguring/Self-Healing of Low Noise Amplifier (LNA)

— Noise Figure, Gain, and Impedance Match



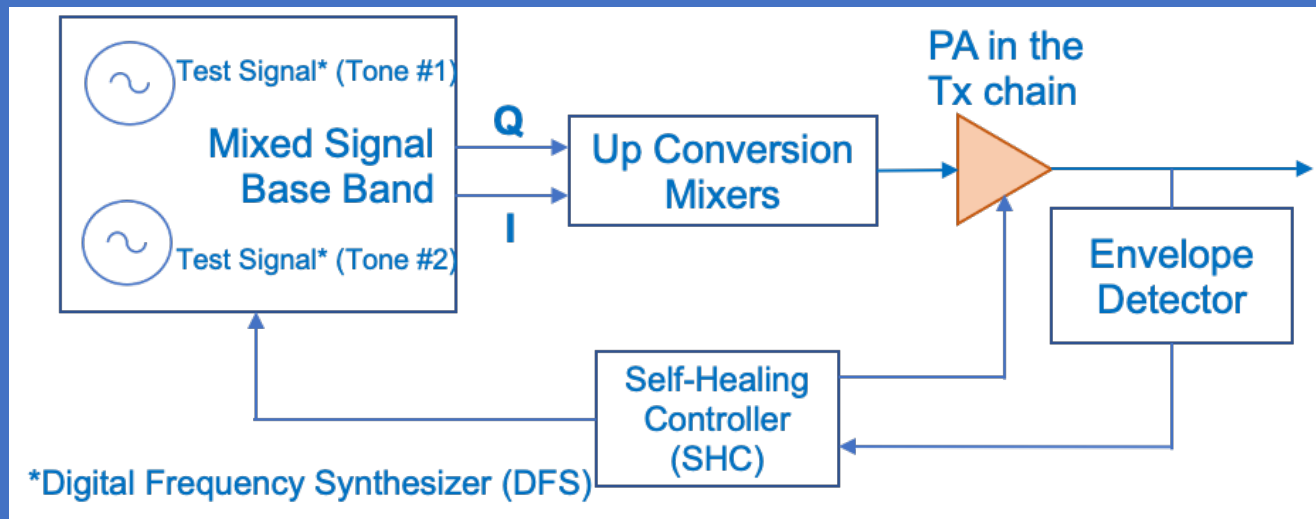
- In a phased array T/R module the LNA operates with low noise figure (NF), high gain, excellent linearity/impedance match, and consumes low power
- Temperature fluctuations causes the NF to change
- By designing a LNA that can reconfigure or tune itself autonomously with temperature change, the degradation in the NF and gain can be recovered

➤ Self-healing solution includes

- Integrating on-chip tunable capacitors, VCO, and an amplitude detector
- Integrating off-chip a DSP with calibration algorithm and an ADC to convert the detector analog output into a digital signal that adjust the tunable capacitor values
- At the desired operating frequency as set by the VCO, the tunable capacitor values are adjusted till amplitude detector output is a maximum

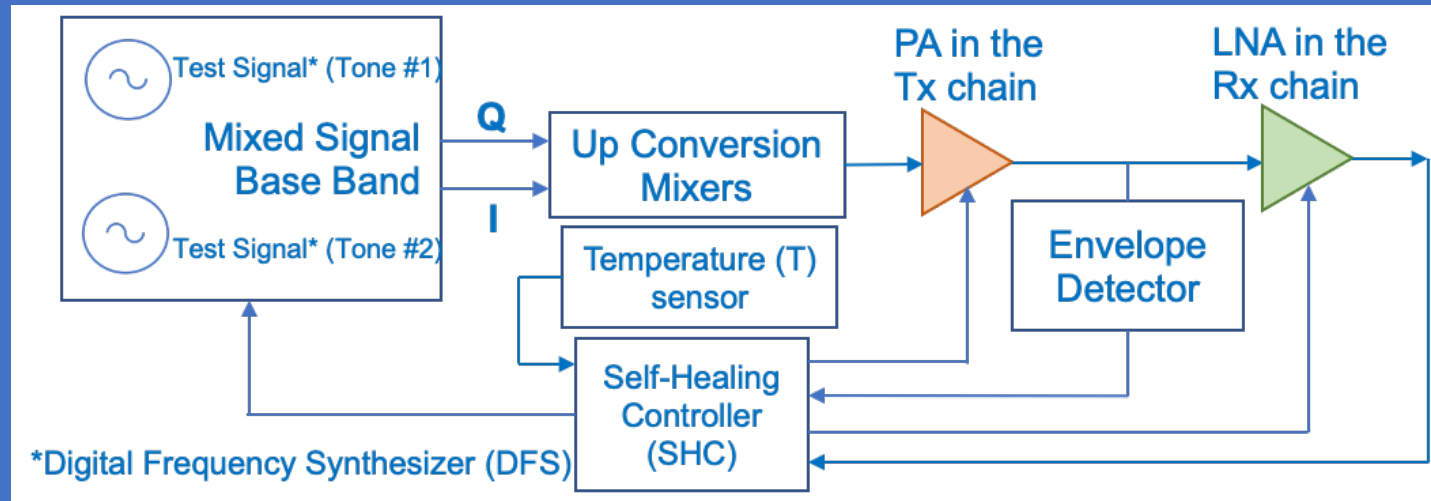
Embedded Autonomous Self-Healing System for a Mixed-Signal Transceiver in a Radio-on-a-Chip — Tx

- The embedded self-healing system continually monitors key transceiver parameters including Tx image rejection, Tx P1dB, Tx OIP3, & the receiver NF & OIP3 throughout the life-time of the radio



- The first step in the Tx self-healing mode is to measure the image frequency rejection ratio by applying the single-tone test signal 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 ≤ -40 dBc. Next, the two-tone signals are applied and the Tx PA voltage and current are adjusted incrementally to reset the gain till the OIP3 is ≤ -40 dBc

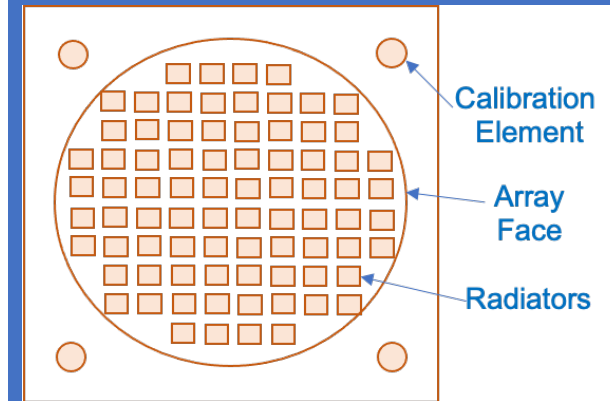
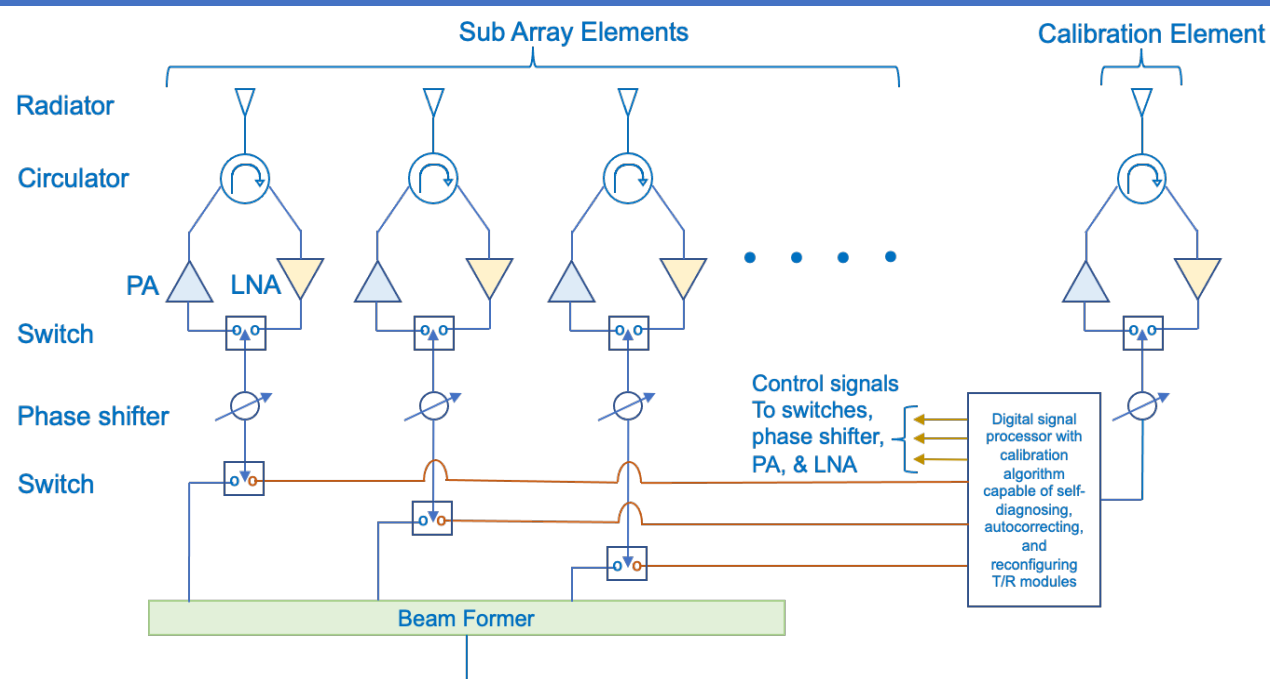
Embedded Autonomous Self-Healing System for a Mixed-Signal Transceiver in a Radio-on-a-Chip — Rx



➤ The self-healing of the Rx is initiated by measuring the gain (G) of the LNA by coupling the two-tone test signals from the Tx. Next, the Tx is shut off and the LNA output noise power (N_0) is measured. Knowing the G , N_0 , Rx bandwidth and T , the NF is estimated. Based on the estimate the SHC adjusts the bias current to the LNA stage to optimize the NF in real time

➤ The SHC occupies an area $\leq 10\%$ of the entire transceiver as overhead & consumes power $\leq 3\%$ as overhead based on 2% duty cycle for self-healing. Hence, the self-healing circuitry has negligible impact on the overall system size, mass, and power

Self-Diagnosing, Autocorrecting, & Reconfiguring/Self-Healing Phased Array T/R Modules



- Self-diagnostic sub-system role: Monitor, detect, & diagnose element failure
- Autocorrection sub-system role: Administers adjustment to the failed elements to bring its performance within acceptable range
- Reconfiguration sub-system role: Adjusts the parameters of the array to compensate for the elements that failed autocorrection

Conclusions & Discussions

- 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

References

Please refer to the conference paper