18.5 A Low-Overhead Self-Healing Embedded System for Ensuring High Yield and Long-Term Sustainability of 60GHz 4Gb/s Radio-on-a-Chip

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The available ISM band from 57-65GHz has become attractive for high-speed wireless applications including mass data transfer, streaming high-definition video and even biomedical applications. While silicon based data transceivers at mm-wave frequencies have become increasingly mature in recent years [1,2,3], the primary focus of the circuit community remains on the design of mm-wave front-ends to achieve higher data rates through higher-order modulation and beamforming techniques. However, the sustainability of such mm-wave systems when integrated in a SoC has not been addressed in the context of die performance yield and device aging. This problem is especially challenging for the implementation of mm-wave SoC's in deep sub-micron technology due to its process & operating temperature variations and limited ft / fmax with respect to the operation frequency.

To address the issue of sustainability in integrated mm-wave transceivers, this paper presents a low overhead self-healing system that can be embedded in an mm-wave transceiver to continually monitor and optimize its performance throughout the lifetime of the radio. The proposed system monitors key transceiver parameters including transmitter image rejection, transmitter P1dB, OIM3, and the receiver noise figure and OIM3. The mm-wave front-end is designed to be extremely tunable allowing for adjustments to be made automatically as the device ages.

Figure 18.5.1 shows the architecture of the self-healing mm-wave transceiver that implements a dual-controller with cautious tracking for the robust control of multiple circuit knobs within the mm-transceivers to meet a target performance specification shown in Fig. 18.5.6. Using the numerically controlled oscillators (NCOs), the probe generator in the self-healing controller (SHC) produces test tones with programmable frequencies and amplitudes to probe the mm-wave transceiver. With known test tones, transceiver impairments, such as image, noise, and intermodulation distortion, can be measured by sensors embedded throughout the transceiver. These sensors measure envelop variations, power level, and temperature. The measured parameters are digitized by the 10b, 5MSps instrument ADC and processed by the parameter estimator (PE), which contains a 128-point FFT processor used for spectral analysis and a statistical processor used to produce reliability measures employed by the dual controller for cautious tracking. To meet aggressive performance metrics such as better than -40dBc of image level and OIM3 in the presence of background circuit noise, the controller through cautious tracking can dynamically adjust the rate of control of various tuning knobs in the transceiver according to the reliability measures from the PE.

The self-healing transmitter is shown in Fig. 18.5.2. The transmitter power amplifier is highly adjustable with bias tuning control spanning over a decade of current as well as independent adjustments for large signal and small signal gain based on output envelope feedback [4]. Before the transmitter DAC, a cascade of real and complex multipliers and adders implement an IQ correction unit to allow programmable adjustment of the I-to-Q DC offset, I-to-Q phase, and I-to-Q relative amplitude for the correction of transmitter image and LO leakage. At the output of the transmitter, a 60GHz envelope detector (square-law device) allows for spectral mixing to measure the image and LO leakage via envelope variation in the transmitted test tones. During the self-healing cycle a single tone is first applied to the TX chain by the NCOs, and the signal-LO product and signal-IM product tone amplitudes are quantized by the instrument ADC and isolated by the FFT. The cautious control block adjusts the I-to-Q phase and amplitude in the IQ correction unit to minimize the LO and image components. Next a two-tone signal is applied and the OIM3-signal term from the envelope detector is compared against the signal square term by the FFT to provide the relative OIM3 levels of the transmitter. The cautious controller then uses a steepest decent approach to adjust the transmitter large signal and small signal gain to minimize the OIM3 levels. In this multi-parameter optimization, the most sensitive knob is adjusted with higher priority. Typical measurements of the transmitter image and OIM3 before and after the healing are shown in Fig. 18.5.3. Also shown are statistical results for 10 chips chosen randomly from a lot with measurements of transmitter image and OIM3 taken before and after the self-healing, demonstrating a drastic yield improvement from 0% to 100%. The self-healing of receiver parameters is shown in Fig. 18.5.4. First, a two-tone is generated by the probe generator through the transmitter. Using the envelope detector as a transmit power sensor, the power delivered to the receiver is computed based on the de-embedded TX-to-RX coupling. From here the tone amplitudes at the receiver output are captured by the SHC's FFT processor to determine the receiver chain gain. Once the gain is obtained the transmitter is shut-down so that the output noise of the receiver chain can be directly measured by the FFT processor. Finally, the temperature is recorded from a temperature sensor so that the thermal noise floor "KT" can be computed (through look-up). As the bandwidth of the receiver chain is fixed by a large passive filter, noise figure can be closely estimated as NF = (No)/(AKTB) Where A is the RX gain, No is the measured output noise of the receiver and B is the receiver bandwidth. Based on the noise figure value computed, the controller adjusts the bias current of each LNA stage [5] to optimize the NF. Figure 18.5.5 shows the convergence of one healing cycle when the SHC is commanded to set the receiver noise figure to <6 dB. As the algorithm converges, the bias control steps (2mA per step) for each stage of the LNA bias adjustment is shown as well as the noise figure. Also shown is the statistical distribution of noise figure for 10 randomly selected chips before and after the self-healing to minimize noise figure.

The overall performance of the self-healing mm-wave radio-on-a-chip is summarized in Fig. 18.5.6. The self-healed radio is capable of supporting up to 16 QAM modulation containing data converters with 30 dB SNDR (including margin for fading) at 2.0 Giga-Symbols/sec operation. The entire self-healing system occupies less than 10% area overhead of the entire transceiver, and requires less than 3% power overhead based on a 2% duty cycle for the self-healing routine. The low power and area overhead make this approach extremely attractive for commercial transceiver design. Beyond the aging and yield issues, the inclusion of the SHC also allows for initial testing and setup of the mm-wave transceiver without the need for costly mm-wave instruments during production. The entire 60GHz self-healing radio on a chip occupies 16mm^2 and consumes 680mW including 198mW for TX, 177mW for RX, 88mW for synthesizers (X2) and 116mW for data converters once initial self-healing is completed.

Acknowledgments:
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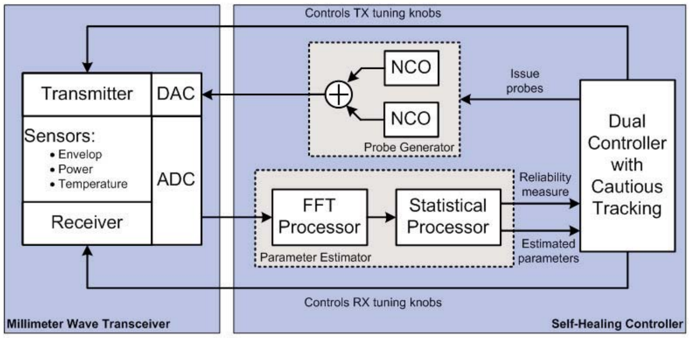

Figure 18.5.1: Self-healing controller (SHC) containing an FFT processor, a Statistical Processor, and a Probe Generator that produces single/two-tone probes via the Numerical Controlled Oscillators (NCO), and a Dual Controller to issue probes and perform cautious tracking.

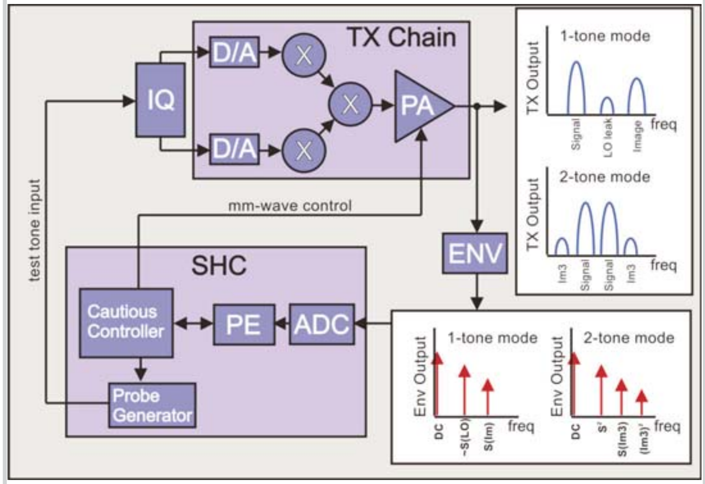

Figure 18.5.2: Transmitter self-healing system showing adjustable transmitter chain, IQ correction unit, envelope detector and SHC.

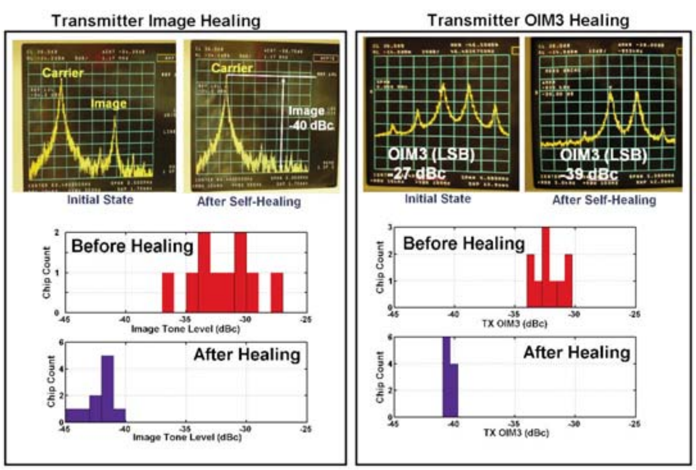

Figure 18.5.3: Example results and statistical distributions for 10 chips of transmitter image tone, and third-order intermodulation products before and self-healing.

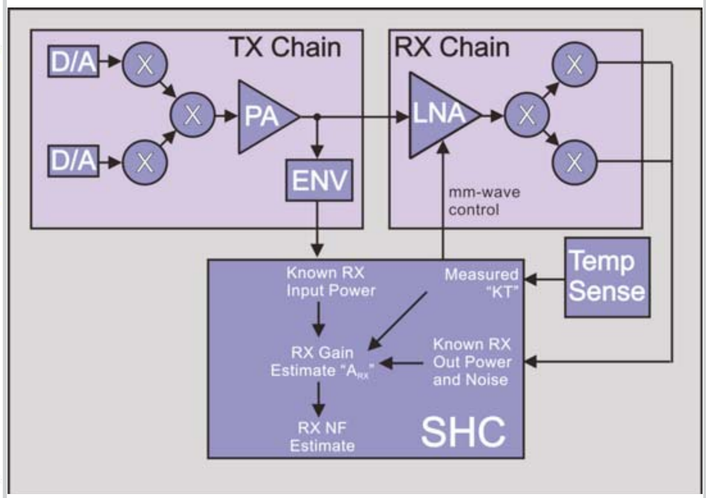

Figure 18.5.4: Receiver self-healing system showing adjustable transmitter chain, adjustable receiver chain, temperature sensor, envelope detector and SHC (self-healing controller).

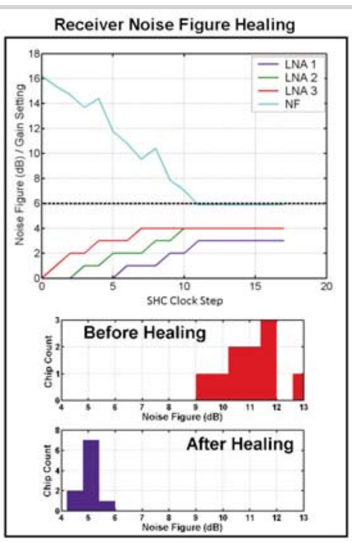

Figure 18.5.5: Statistical Results of receiver noise figure without/with self-healing and convergence of noise figure healing.

Baseline Transmitter	Baseline	Target	Post Healing	Post-Healing Performance Yield
Output P1dB (dBm)	9.5 (+/- 3.1)	10	13.15(+/-0.55)	100%
Output OIM3 (dBc)	-32.50 (+/-5.1)	-40	-42.56 (+/-0.54)	100%
Output Image (dBc)	-32.35(+/-2.5)	-40	-42.6 (+/-1.6)	100%
RF Bandwidth (GHz)	5.0	N/A	5.0	N/A
Baseline Receiver				
Noise Figure (dB)	10.48(+/-1.1)	6.0	5.5(+/-0.5)	100%
RX OIM3 (dBc)	-43.2(+/-2.9)	-40 dBc	N/A	100%
Baseline Synthesizer				
Phase Noise (dBc/Hz @ 1M)	-97	-95	N/A	N/A
Self Healing Circuits				
Power Consumption (mW)	N/A	13	2%	N/A
Area Overhead (%)	N/A	10	6.3	N/A

Figure 18.5.6: Summary of self-healing transceiver showing the baseline (pre-healing) performance, target performance supporting 16QAM, post-healing performance, and performance yield based on 10 measured die achieving the target performance.

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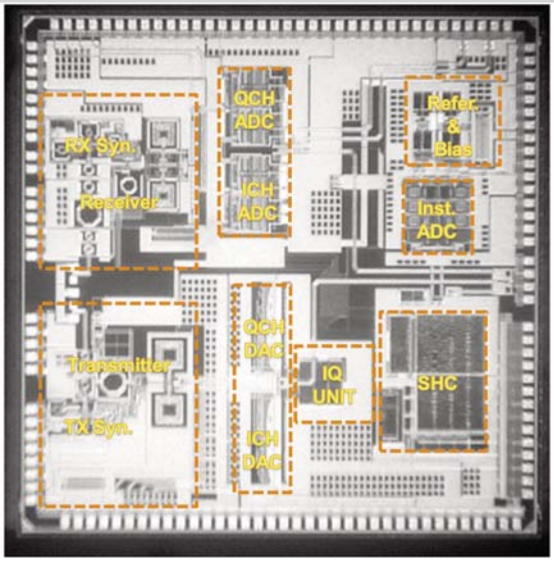

Figure 18.5.7: Die photo of self-healing 60GHz radio-on-a-chip.

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