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A 65nm Resonant Electro-Quasistatic 5-240uW Human Whole-Body Powering and 2.19uW Communication SoC with Automatic Maximum Resonant Power Tracking

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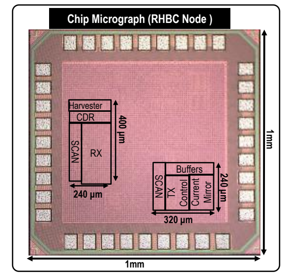
Applications like Connected Healthcare through physiological signal monitoring and Secure Authentication using wearable keys can benefit greatly from battery-less operation. Low power communication along with energy harvesting is critical to sustain such perpetual battery-less operation. Previous studies have used techniques such as Tribo-Electric, Piezo-Electric, RF energy harvesting for Body Area Network devices, but they are restricted to on-body node placements. Human body channel is known to be a promising alternative to wireless radio wave communication for low power operation [1-4], through Human Body Communication, as well as very recently as a medium for power transfer through body coupled power transfer [5]. However, channel length (L) dependency of the received power makes it inefficient for L>40cm. There have also been a few studies for low power communication through the human body, but none of them could provide sustainable battery-less operation. In this paper, we utilize Resonant Electro Quasi-Static Human Body Communication (Res-EQS HBC) with Maximum Resonance Power Tracking (MRPT) to enable channel length independent whole-body communication and powering (Fig.1). We design the first system to simultaneously transfer Power and Data between a HUB device and a wearable through the human body to enable battery-less operation. Measurement results show 240uW, 28uW and 5uW power transfer through the body in a Machine-Machine (large devices with strong ground connection) Tabletop (small devices kept on a table, as in [5]) and Wearable-Wearable (small form factor battery operated devices) scenario respectively, independent of body channel length, while enabling communication with a power consumption of only 2.19uW. This enables >25x more power transfer with >100x more efficiency compared to [5] for Tabletop and 100cm Body distance by utilizing the benefits of EQS. The MRPT loop automatically tracks device and posture dependent resonance point changes to maximize power transfer in all cases.

In the EQS regime, signal wavelength is significantly larger than the human body-size, enabling channel length independent loss and physically secure communication through signal confinement. The parasitic capacitances associated with the forward (device cap C_p) and return path (C_{ret}) are the primary contributors to channel loss (Fig.2) [1]. Previous studies primarily used 50Ω receiver termination, resulting in ~80dB loss in the MHz range. EQS HBC utilizes high impedance termination [4] to reduce the channel loss to the 40-60dB, which is sufficient for communication but not powering. Resonant cancellation of the parasitic capacitances (Fig. 2) further reduces the channel loss to ~20dB, enabling whole body power transfer, for the first time, due to constant channel loss across the body. Series Resonance (HUB side) cancels C_p and boosts the transmitted voltage by a factor Q, increasing V_{TX}, improving whole-body power delivery. Simultaneous Parallel Resonance at the receiver helps to cancel C_L, C_{ret} and improves V_{RX}, providing a Q^4 boost in maximum received power ($P_{RX_{max}}$), making it ideal choice for HUB to NODE powering. For Communication, however, the FoM V_{RX}/P_{TX}, is maximized with Parallel Resonance at both ends, allowing a Q^3 boost, due to exhibiting a high impedance and hence transmitter current minimum at resonance, which helps transmitter power to be reduced by 33%, compared to simple EQS TX with 30pF load (Fig.3).

The resonant frequency is highly dependent on Device cap (C_p), return path cap (C_{ret}) and body cap (C_{Body}), which exhibits significant inter-device, posture-dependent and inter-human variability. This necessitates an MRPT loop to ensure maximum power delivery at all cases (Fig. 2). The HUB uses a dedicated frequency scanning phase before transmit phase to lock the resonant frequency automatically before power transmission, ensuring high P_{RX} and efficiency(η).

Fig. 3 shows the overall system architecture for the HUB and NODE. The battery-operated HUB consists of a Power Transmitter (series resonance) and a TRx link (parallel resonance). An on chip digitally controlled current starved oscillator generates the duty cycled corrected clock (0.1-5MHz) during both the scanning and transmission phase. A fully synthesizable digital controller (HUB TX Unit) coordinates scanning and transmit phase for powering, and communication. An automatic feedback loop (MRPT) samples the peak value of the transmitted signal during scanning phase through a capacitive divider network and a peak detector consisting of a passive Envelope Detector (ED) followed by a sampler. Sampling and peak comparison between successive frequencies are done without any memory, using 3 non-overlapping clocks generated by the fully digital Adaptive Clock Divider. The transmission phase begins after the scanning phase with the frequency locked at resonance (Fig. 3). The Communication receiver utilizes a 2-stage current starved self-biased common source amplifier operating at a few MHz carrier frequency (fc.). A 4-stage gate biased tunable passive ED is used as demodulator. A high f_c to baseband (f_{BB}) ratio (>40) is necessary for satisfactory ED operation with BER <10^{-5}. A StrongARM Latch is used to digitize the signal at $10f_{BB}$ rate followed by an oversampling all digital CDR for DATA & CLK. An Energy Harvester at the NODE side stores the incoming power on a capacitor to provide a 0.5V supply (Fig. 5) enabling perpetual NODE communication.



The SoC is fabricated in 65nm CMOS technology (Area =0.13mm^2). Fig.4 shows measured results on how series resonance at HUB Tx helps maximize transmit voltage and hence P_{TX}. P_{RX} and η are shown as function of HUB TX supply voltage for Machine-Machine and Tabletop cases. The maximum received power is measured by varying the resistive component of the load at the receiver end. The peak received power in Machine-Machine, Tabletop and Wearable-Wearable scenario is 240uW (RL=1kΩ) with 37% efficiency, 28uW (RL=20kΩ) with 3% efficiency and 5uW(80kΩ) with 7% efficiency, respectively. Machine-Machine is most efficient with Series-EQS (no C_{ret}), and Tabletop is most-efficient with Series-Par Resonance. The Comm Tx consumes only 2.19uW power during data communication at parallel resonance while driving a 30pF load at 20Kbps DR and ~1MHz fc., 33% lower than EQS-HBC due to cancellation of C_P. The HUB control unit and the digitally controlled starved oscillator consumes 0.3uW average power. The receiver operates at 10^{-5} BER at 20kbps data rate with a 0.55UI timing margin (Fig.5). The receiver shows a sensitivity of -60dBm (318uV) and -52dBm(794uV) with 1kbps and 20kbps data rate, respectively. At the lowest power mode, the receiver consumes only 72nW power. Powering and Data Communication timing waveforms (Fig.5) show automatic MRPT & successful demodulated data, respectively.

Fig.6 shows comparison with other works (either only powering or only communication). This design achieves η=37% for machine-machine, η=3% for a tabletop and η=7% for a wearable-wearable interaction scenario, independent of channel length (i.e. whole-body powering) and >4.5x lower maximum transmitted power, increasing safety. This is >100x improvement in body coupled power transfer efficiency and >10x improvement in peak power transfer for longer channel lengths as shown in the comparison table in Fig.6. The current design utilizes the body channel for the first time to enable simultaneous data communication, at 2.19uW power budget, along with whole-body power transfer making battery-less perpetual body nodes a reality.

References:

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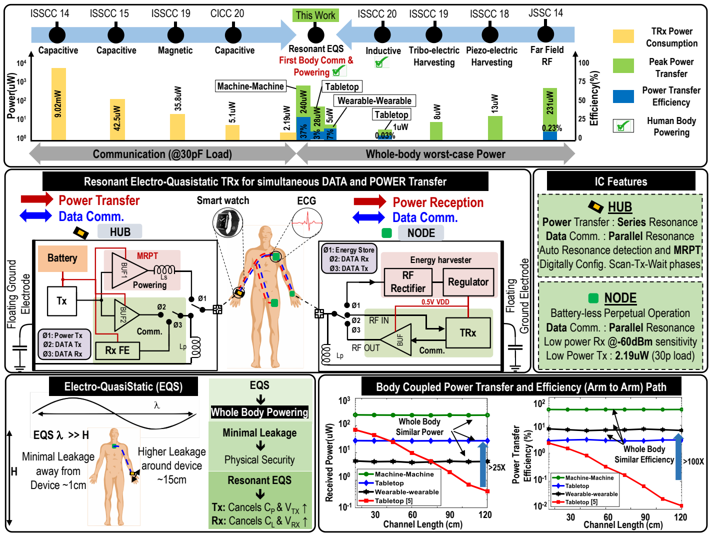

Fig. 1. Resonant Electro Quasi-Static Human Whole-Body Powering and Communication: Detailed architecture and comparison with previous Body Area Network communication and powering.

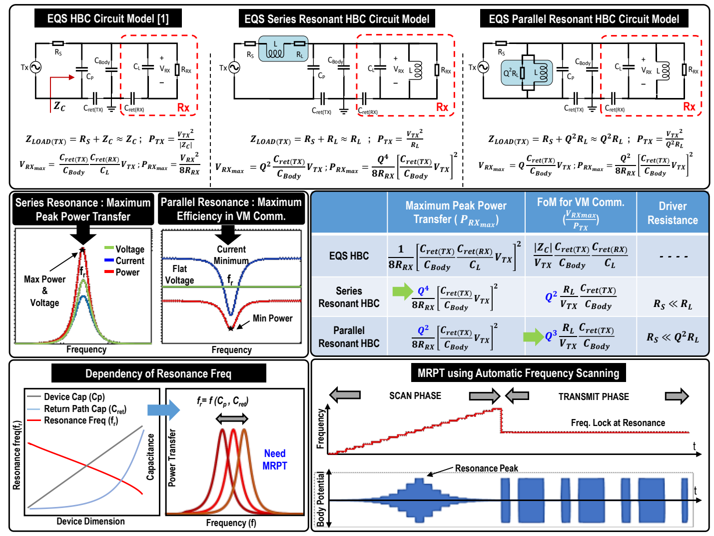

Fig. 2. Theoretical analysis of voltage & power transfer of different resonant techniques. Variation of resonant frequency with physical parameters and auto Maximum Resonant Power Tracking (MRPT).

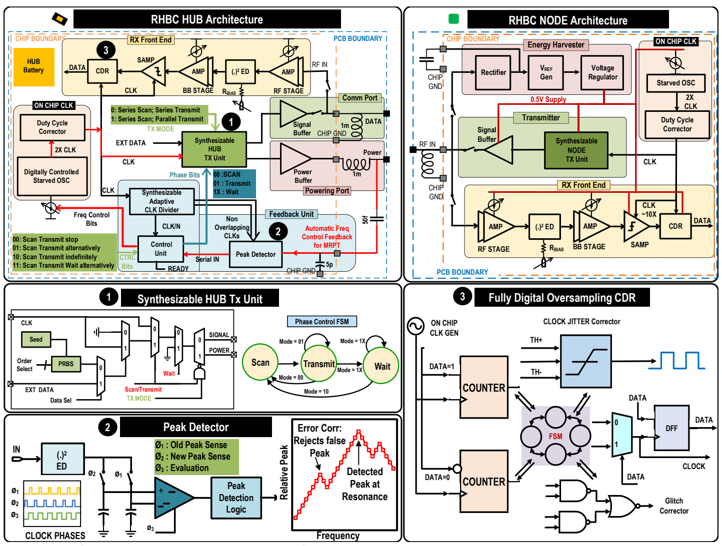

Fig. 3. Overall architecture of the Hub and the Node device. Detailed design of the Hub Tx unit, peak detector, and the oversampling Clock Data Recovery circuit.

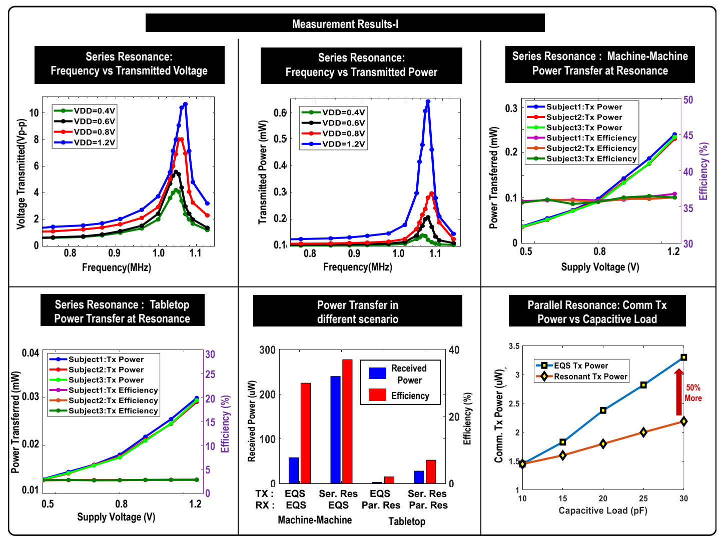

Fig. 4. Measured received power & efficiency of power transmission. Lesser transmitter power consumption during communication at parallel resonance due to cancellation of the load capacitance.

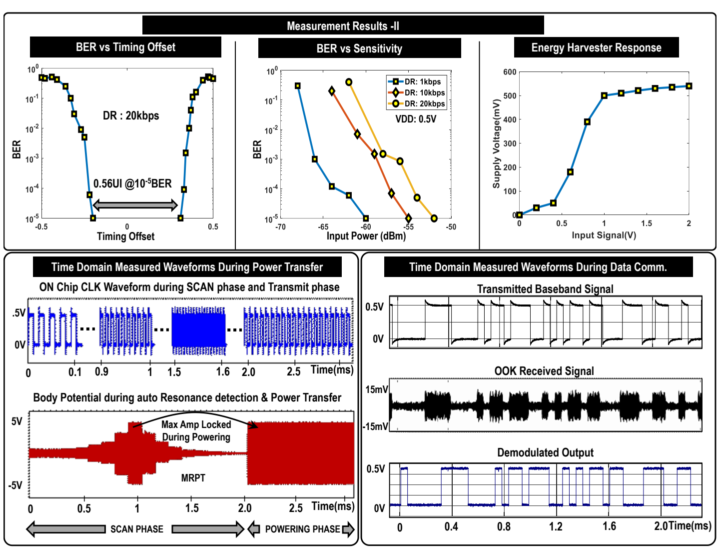

Fig. 5. Receiver bathtub curve & sensitivity analysis of the receiver. Time domain snapshot of the scanning phase at the transmitter and data communication between transmitter and receiver.

Comparison Table with State-of-the-Art HBC Transceivers and Energy Harvesting Techniques for Wearables

	Powering & Comm	Only Powering				Only Communication			
	This Work	J. Li ISSCC '20	I. Park ISSCC '18	M. Meng ISSCC '19	L. Xia JSSC '14	S. Maity CICC '19	H. Cho ISSCC '15	J. Park ISSCC '19	J. Lee ISSCC '14
Technique	Resonant EQS (Body Coupled)	Body-coupled + Ambient	Tribo Electric Harvesting	Piezo-electric Harveting	Far Field RF Harvesting	Capacitive	Capacitive	Magnetic	Capacitive
Process	65nm CMOS	40nm CMOS	180nm BCD	0.35um CMOS	65nm CMOS	65nm CMOS	65nm CMOS	65nm CMOS	65nm CMOS
Operating Freq	0.5-2 MHz	40 MHz Tx 50/60 Hz	100 Hz	90-160 Hz	904.5 MHz	0.1-1 MHz	10/13.56 MHz	40 MHz	40-80 MHz
Human Body Powering	**Yes**	**Yes**	No	No	No				
Power Delivered	240 uW (Machine-Machine) **28 uW** (Tabletop), Whole Body 5uW (Wearable-Wearable)	**1 uW** (100cm, Tabletop) 100 uW (~cm)	2-8 uW	2-13 uW	231.6 uW(<3m)				
Transmit Power	**650 uW** (Max) → **Safer**	**3mW**	NA	NA	20 dBm				
Efficiency	37%(Machine-Machine) **3%**(Tabletop) 7% (Wearable-Wearable)	**0.03**-3.33%	NA	NA	0.232%				
Coverage	Full Body (Distance **Independent**)	Full body (Distance **Dependent**)	Joint and feet	Limbs	0.9-9m (antenna dependent)				
Modulation	OOK					OOK	OOK	OOK	Walsh Coding
Supply Voltage	0.5					0.5	0.8	0.6	1.1
Data Rate	1-20Kbps					1-20Kbps	100Kbps	5 Mbps	60 Mbps
Tx Power	1.3uW (10p load) 1.5uW (20p load) **2.19uW (30p load)**					**3.7 uW** @1MHz f_c (30p load)	21 uW	35.8uW	1.85mW
Rx Power	**72nW** (with on-chip OSC and CDR)					**1.4 uW**	42.5 uW	24uW	9.02mW
Sensitivity	-60 dBm @10^{-5} BER					-64dBm @10^{-3} BER	-60 dBm @10^{-5} BER	-56 dBm @10^{-3} BER	-58 dBm @<10^{-5} BER

Fig. 6. Comparison with state-of-the-art HBC Transceivers and energy harvesting techniques, showing the first work to simultaneously transmit power and communicate data.