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End-to-end design of ingestible electronics

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Supplementary Table 1. Summary of commercial and custom analog front end circuits.

Modality	Type	Name/ Reference	DC Current [μA] (Sampling Rate)	ADC Capabilities	Supply Voltage [V]	Total Power [μW]	Area [mm^2]
Optical	Commercial	AFE4404	600 (100 S/s)	24-bit, 1 kS/s	2	1200	2.6×1.6
	Commercial	MAX86141	80 (256 S/s)	19-bit, 4096 S/s	1.8	144	2.05×1.85
	Custom	[1]	117 (360 S/s)	10-bit, 360 S/s	1.2	140.4	2×2
	Custom	[2]	9 (NR)	10-bit, 225 kS/s	1.55	13.95	2×1
Electrochemical	Commercial	NJU9101	250 (1 kS/s)	16-bit, 2 kS/s	2.4	600	4×4
	Commercial	AD5941	6000 (200 kS/s)	16-bit, 1.6 MS/s	2.8	16800	3.6×4.2
	Custom	[3]	2.5 (0.2 S/s)	16-bit, 0.2 S/s	1.2	3	0.36
	Custom	[4]	58 (1 kS/s)	12-bit, 10 kS/s	1.8	104.4	0.47
Bioimpedance	Commercial	ADS1192	280 (500 S/s)	16-bit, 8 kS/s	2.7	756	5×5
	Commercial	MAX30001G	150 (512 S/s)	20-bit, 512 S/s	1.1	165	2.75×2.95
	Custom	[5]	36 (10 kS/s)	9-bit, 1 MS/s	1.8	64.8	0.24
	Custom	[6]	33 (128 kS/s)	12-bit, 128 kS/s	1.2	39.6	0.738

NR – not reported

Supplementary Table 2. Summary of commercial and custom transceiver (TRX) modules.

Modality	Technology (Frequency)	Name/ Reference	Modulation	TX/RX Data Rate [Mb/s]	TX (output power)/RX DC Current [mA]	Supply Voltage [V]	TX/RX Energy Efficiency [nJ/bit]	Area [mm^2]	External Components
RF	BLE & Zigbee (2.4 GHz)	nRF5340	FSK/ PSK	2	3.2 (0dBm) /2.6	1.8	2.7/2.2	4.4×4.0	MN,ANT, XTAL
		STM32WB	FSK/ PSK	2	5.2 (0dBm) / 4.5	1.8	4.4/3.8	5.1×5.1	MN,ANT, XTAL
		CC2650	FSK/ PSK	2	6.1 (0dBm) /5.9	1.8	5.5/5.3	5.0×5.0	MN,ANT, XTAL
	BLE (2.4 GHz)	MAX3266	FSK	2	4.3 (0dBm) /3.3	1.8	3.7/2.8	4.2×3.8	ANT, XTAL
		QN908	FSK	2	3.5 (0dBm) /3.5	1.8	2.8/2.8	3.3×3.2	MN,ANT, XTAL
		[7]	FSK	1	5.4 (0dBm) /2.3	1	5.4/2.3	0.85	ANT, XTAL
		[8]	FSK	1	3.7 (0dBm) /2.75	1	3.7/2.8	1.9	ANT, XTAL
		[9]	FSK	1	2.9 (-3dBm) /2.3	1	2.9/2.3	1.64	ANT, XTAL
	MICS (400 MHz)	ZL70102	FSK	0.8	5.3 (-3dBm) /4.3	2.8	18.5/15	4.3×3.2	MN,ANT, XTAL
		[10]	FSK	0.2	3.1 (-6dBm) /1.5	1	15.5/7.5	3.5×3.8	ANT
		[11]	PSK	4.5	2.3 (-10dBm) /2.2	1	0.6/0.5	1.7×1.8	MN,ANT, XTAL
	ISM (915 MHz)	[12]	OOK	0.25	0.135 (NR) /NR	1.55	0.8/NR	0.003	None
	ISM (915 MHz)	[13]	PPM	0.03 /0.06	0.05 (-27dBm) /1.55	4	2/29.6	2.2×1.2	ANT
	Backscatter	[14]	OOK	0.125 /NR	0.1 (NR) /NR	1.8	1.4/NR	7.5×12	ANT
Ultrasonic	Other	[15]	OOK	0.1 /0.025	0.18 (NR) /NR	1	1.8/NR	2.6×6.5	Piezo
Magnetic	Other	[12]	OOK	NR /$2*10^{-11}$	NR /0.175	1.55	NR /$13*10^{3}$	0.9×0.9	Magnetic Sensor

NR – not reported, MN – matching network, ANT – antenna, XTAL – crystal

Supplementary Table 3. Summary of powering techniques.

Modality	Type	Output Voltage	Size [mm^2 \ mm^3]	Capacity / Power	Safety
Battery	Li-ion[16,17]	3 V	Ø 4.8×1.2 Ø 6.8×2.1	1 mAh 5.5 mAh	Low
	Silver oxide[18,19]	1.55 V	Ø 4.8×1.6 Ø 6.8×2.8	7.5 mAh 28 mAh	Moderate
	Solid-state[20]	1.5 V	4.4×3×1.1	100 μAh	Moderate
	Transient[21]	2.5 V	8×10×0.3	0.6 μAh	High
	Flexible[22]	3.9 V	2.25×1.7×0.13	5.6 μAh	Moderate
Energy harvesting	Piezoelectric[23]	0.1 V	25×20×0.075	NR	High
	Triboelectric[24]	0.2 V	16×12×2.5	40 μW	High
	Galvanic[25]	0.15 V	3×10×0.25	7 μW	High
Power transfer	Acoustic[15]	0.2 V	0.9×0.9×0.5	>200 μW	Moderate
	RF[26]	NR	6.8×6.8	>120 μW	Moderate

NR - not neported

Supplementary Table 4. Summary of localization techniques for ingestibles.

Modality	Components in the pill	Components in the external station	Pill components' power consumption	External station's power consumption	Complexity	Accuracy
Imaging	None	MRI, CT, X-ray or ultrasound scanner	None	High (kW-level)	High	High (hundreds of μm)
Environmental	pH, temperature and O_2 sensors	None	Low (μW-level)	None	Low	Low (organ-level)
RF	RF transmitter	RF receiver	High (mW-level)	Moderate (mW-level)	High	Low (few cm)
Ultrasound	Ultrasonic transducer	Ultrasonic transducer	Moderate (sub-mW)	Moderate (sub-mW)	Moderate	High (sub-mm)
Magnetic I	Permanent magnet	Magnetic sensors	None	Moderate (mW-level)	High	Moderate (few mm)
Magnetic II	Magnetic sensor	Permanent magnet or electromagnet	Low (μW-level)	Moderate / High (tens to hundreds of mW)	Moderate	High (hundreds of μm)

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