A WBAN 802.15.6 Compliant Multi-Band Re-configurable Transceiver for Medical Applications

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ABSTRACT
The first WBAN 802.15.6 compliant radio system working in MICS/ISM band is reported in this paper. The radio system consists of a transceiver IC and a FPGA-based digital baseband, and is designed for medical applications like wearable and implantable sensors. The transmitter adopts a PLL-based polar architecture, supporting data rate from 10kbps to 4.5Mbps, consuming 2.28mW from 1V VDD supply. The zero-IF based receiver is programmable in terms of noise performance and power consumption for different application scenarios, resulting 2.2mW for noise-figure-optimized mode and 1.9mW for power-efficient mode.

General Terms
Algorithms, Measurement, Documentation, Performance, Design, Experimentation, Standardization.

Keywords
802.15.6, low power, sensor.

1. INTRODUCTION
Healthcare has always been an important issue in the modern society, thus attracts enormous attention in industry and academy. The emerging wireless body area network (WBAN) technology shows a promising future for low-cost, easy-access and more preventive healthcare system. In order to accommodate the WBAN solution, the IEEE802.15.6 standards was released in 2012 [1].

As compared to the other candidate technologies/standards, 802.15.6 standard offers very attractive features

- Low power consumption and low peak power
- Variable data rate
- Reliable and secure wireless communication

while Bluetooth low energy (BLE) has a fixed data rate and faces strong co-existence from ISM band technologies, ZigBee offers lower data rate and suffers from the same co-existence issue and Zarlink is still proprietary.

Therefore, the implementation of the 802.15.6-compliant radio system becomes crucial. Prior art [2,3] have addressed 802.15.6-compliant radios in the 2.36GHz ISM band, which falls in a very crowded spectrum. In this paper, we propose the first 802.15.6-compliant radio in the 402MHz-405MHz MICS band and 420MHz-450MHz ISM band. The system consists of the transceiver IC [4], the FPGA-based digital baseband (DBB) and the MCU to interface with applications. The proposed system is highly re-configurable, by means of circuit techniques and optimized architecture design, in order to support variable modulation scheme, data rate and link budget within the power budget, as defined in the standard.

2. SYSTEM ARCHITECTURE

2.1 802.15.6 in MICS/ISM Band

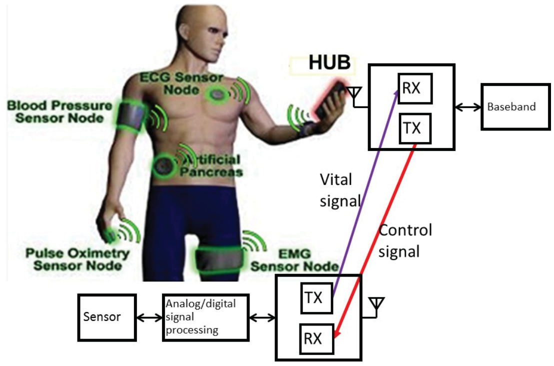

Figure 1 Application of the proposed radio

IEEE802.15.6 proposes several frequency band for implementation and the proposed radio system works in the MICS band (implantable) and the ISM band (wearable). The frequency band choice is based on the following reasons. The power consumption of a WBAN device is of primary concern since it determines the operation time, the form factor (dominated by the battery), the constant performance over time and etc. Naturally, for transceiver analog front-end, 400-MHz circuit consumes substantially lower power than 2.4GHz counterpart, therefore is more power efficient. Operating at 400MHz allows more digital implementations since full swing signal is available at no extra cost, and digital implementation allows easier technology migration and IP reuse. Further, due

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to the lower operating frequency, off-chip matching network is less sensitive to parasitic values and components value spread, as compared to the GHz-applications. Finally, the choice of 400MHz allows hardware reuse for both lower ISM band and MICS band, offers immunity to strong interferences around 900MHz and 2.4GHz, provides a world-wide-compliant solution and supports both implantable and wearable sensors.

2.2 Application Senarios

The target medical application aimed by the proposed radio operates between attachable/implantable medical devices and a HUB, monitoring different vital signs, controlling injected drugs, and sending implant device signals as shown in Figure 1. The medical devices include sensors, drugs, and implantable devices. Vital signals, such as EEG, ECG, eye movement, etc., are monitored by sensors worn as necklace, belt, bracelet, or implanted in the body. Injected drugs and implantable medical device include endoscope capsule, drug delivery capsule, artificial pancreas, etc., controlled and monitored via the HUB by the remote doctors.

2.3 System Overivew and Specifications

As in Figure 1, we propose one-transceiver solution for both HUB and sensors nodes/medical devices. The sensor node consists of a sensor, signal processing block either in analog or digital domain, and a transciever to deliver the upconverted vital signal to antenna, or to receive the control signal from the HUB. The HUB consists of a transceiver, receiving vital data from sensor nodes or delivering control signal to sensor nodes, and the digital baseband for further data processing. Depending on operating at the HUB side or the sensor side, and on the type of the sensor, the transceiver needs to support different data rate as defined by 15.6 standard in Table 1. Further, to accommodate low-data-rate control signal and high-data-rate image signal like EEG, proprietary mode is also implemented to further extend the data rate to 10kbs~4.5Mbps. Therefore, a re-configurable architecture is very important to optimize between power efficiency and circuit complexity.

Table 1 Transceiver specifications

Mode	15.6-compliant				Low Power (LP)	High Speed (HS)
Frequency [MHz]	402 - 405			420-450	402 - 450	
Modulation	π/2 DBPSK	π/4 DQPSK	π/8 D8PSK	GMSK	π/2 DBPSK	π/8 D8PSK
Data rate [kb/s] (w/o BCH coding)	187.5	375	562.5	187.5	11.7	4500
Spreading factor	1	1	1	1	16	1
RX sensitivity[dBm]	-92	-89	-83	-84	-95	-83
TX output power [dBm]	≤ -16			≥ -10	≤-16	≤-16

Table 1 also shows the sensitivity specification and the TX output power in each mode. TX output power is well defined in 802.15.6 standard, and (Pout,tx – sensitivity) needs to be greater than the link budget as shown in Figure 2. For proprietary mode, sensitivity is derived based on same transceiver analog front end (AFE) performance. Considering the shadowing effects from human body, calculations are carried out based on outside-to-inside and surface-to-surface human-body models [5]. Two cases are considered: implantable sensors 1cm inside the human body, and wearable sensors. In both case, 1-meter outside human body link is assumed as shown in Figure 2. Path loss in/around human body channel, instead of free-space channel, is used in the calculation. Further, a few more factors, like multi-path fading loss and digital implementation losses, are also considered. The calculation results show that the sensitivity needs to be tightened up to -92dBm for all the standard-compliant modes, in order to cover the target 1-meter wireless range. For proprietary LP mode, sensitivity can tradeoff with power consumption.

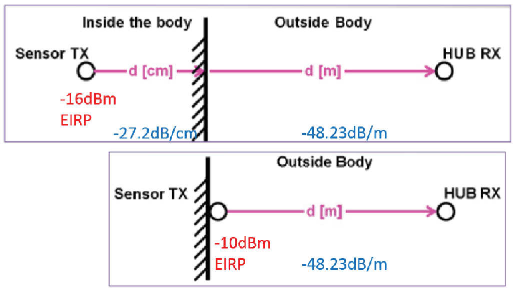

Figure 2 link budget calculation (a) implantable sensor in MICS band; (b) wearable sensor in WMTS/ISM band

2.4 Transceiver Architecture

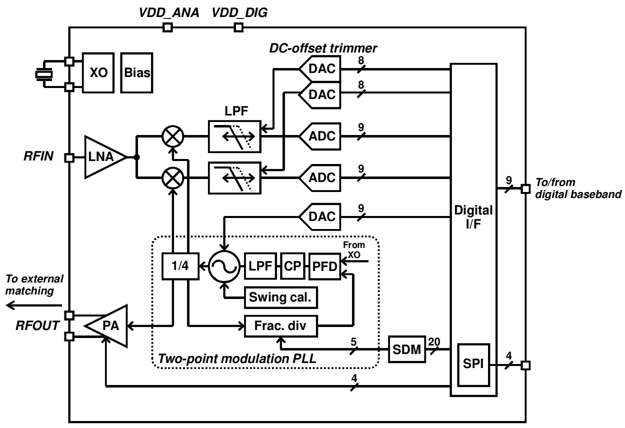

Figure 3 Transceiver architecture

The transceiver analog frontend (AFE) is shown in Figure 3. The PLL-based polar transmitter achieves phase/frequency (FM) and amplitude modulation (AM) in two paths. As compared to conventional mixer-based transmitter, the PLL-based TX benefits from the lower power consumption, however suffers from the limited bandwidth and the AM/Phase Modulation (PM) mismatch. The data bandwidth is extended by adding a high bandwidth path, realized by a FM-DAC. The AM/FM mismatch is tackled by implementing the AM path digitally by digitally-controlled PA (DPA). In this case, the mismatch between AM/FM is easily calibrated in the digital path.

The receiver adopts a zero-IF structure, which avoids the image rejection issue and lowers the power consumption, however faces DC offset and 1/f noise issues. The DC offset issue is relaxed by adding a DC-offset calibration loop and the 1/f noise is optimized at the circuit level. The RX chain consists of the low-noise-amplifier (LNA) to amplify the RF input signal, IQ mixer to downconvert the RF signal, and the 3-stage butterworth low-pass-filter (LPF) to further amplify the signal and to suppress the blocker. The analog signal is converted to digital signal by 9-bit SAR ADC and the ADC output is delivered to the FPGA-based digital baseband (DBB) via a digital interface, for further processing.

2.5 Re-configuratble Transmitter

The transmitter is highly re-configurable, supporting different modulation schemes. The modulation is achieved at three points in a polar transmitter as shown in Figure 4. The baseband modulation signal is split into AM code and FM code. The AM code turns on/off certain number of PA units, realizing AM. The PM code modulates the VCO output frequency in two ways: slow modulation in PLL for signal below the PLL bandwidth, and fast/direct modulation via FM-DAC for signal above the PLL bandwidth. For constant envelope, GMSK, the AM path output a fixed code. For better overall efficiency, switching PA is employed in place of linear PA in the PA array, offering better power efficiency for both modulation schemes. For non-constant envelope modulation, DXPSK, all the three points are enabled. In order to support different DXPSK modulation schemes with optimum power efficiency and circuit complexity, a re-configurable FM-DAC and a variable gain VCO are combined and the principle is explained as below.

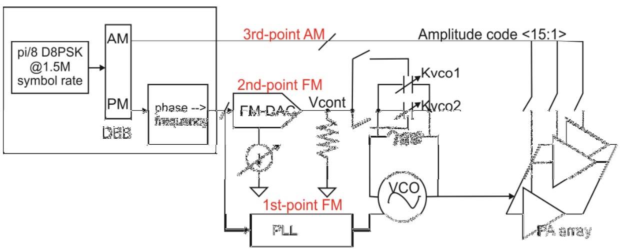

Figure 4 3-point TX:AM, FM-DAC and VCO

Table 2 FM-DAC specification summary

Mode	High data mode	15.6 MICS	15.6 ISM
Symbol rate (k)	1500	187.5	187.5
Modulation scheme	D8PSK	D8PSK	GMSK
EVM	7.5%	7.5%	20%
Fdev, Range kHz	+/- 6000	+/- 800	+/-50
Fdev, Resolution (bits)	9	9	7
Kvco (MHz/V)	30	3	3
Ibias(uA)	5	5	0.4
$Vcont_{pp\text{-}diff}$ (mV)	400	400	34

The FM-DAC serves as the second point PM, extending the modulation bandwidth beyond the PLL bandwidth (100kHz). As in Figure 4, the PM information is translated into frequency information in DBB. The FM-DAC acts as a bridge between DBB and the VCO, converting the digital frequency information into analog control voltage, Vcont. The VCO frequency is tuned via the varactors, and the frequency deviation is $V_{cont} \times K_{vco} = F_{dev}$. By such, the phase modulation is realized. Modulation scheme, symbol rate and modulation accuracy (EVM or frequency error) determines the range and the accuracy (number of bits) of Fdev.

System level simulation based on the block diagram in Figure 4 is carried out to determine the range and the resolution of Fdev. The results are shown in Table 2. The maximum range of Fdev is +/-6MHz, while the minimum resolution is $100kHz/2^7$~1kHz. Without re-configurable structure, a single FM-DAC with +/-6MHz range and 1kHz resolutions is needed, resulting a 16-bit DAC at the expense of power consumption, chip area and circuit complexity. Alternatively, by adopting different varactors (Kvco) in different modes; and different Ibias to achieve different Vcont, four different modulations are supported without introducing more complicated circuit and more power consumption.

3. MEASUREMENT RESULTS

The transceiver is implemented in CMOS 40nm technology and the die photo is shown in Figure 5. The chip measures 1.7mmX1.8mm.

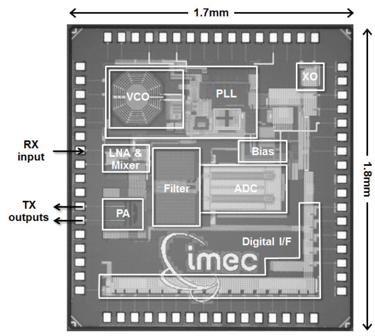

Figure 5 Die photo of the Transceiver IC

3.1 Transmitter Evaluation

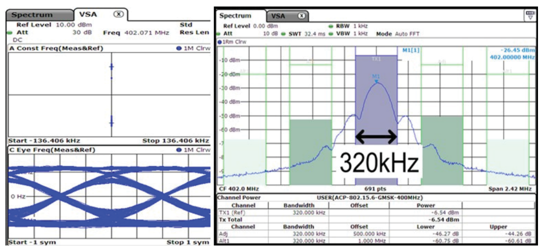

Figure 6 TX measurement: GMSK

The GSMK mode is evaluated first. Figure 6 show that the frequency deviation is only 5%@-6.5dBm Pout and can be further reduced to -2.83%@-10dBm Pout, vs. standard specified 20%@-10dBm. The frequency deviation stays stable at different output power level and different frequencies. The measured ACPR is -44dBc, (which is better than the required IEEE15.6 ACPR requirements for the hub and the sensor.

The π/8-D8PSK mode is evaluated for both standard compliant mode and the proprietary mode. The measured EVM and ACPR are shown in Figure 7. For symbol rate 187.5ksps, with -17.3dBm output, the EVM achieved is 3.5%, and the ACPR is -32dBc. A pulling effect has been observed between VCO and the PA which degrades the ACPR. This effect can be relaxed by pushing more current in the PLL and the VCO, resulting 2.12mW total power consumption. The -32dBc ACPR is achieved by opening up the PLL bandwidth, thus introducing better suppression at the adjacent channel, at the cost of higher power consumption.
For the high speed data rate mode (4.5Mbps with π/8 D8PSK), the occupied bandwidth is 2.4MHz and the symbol rate is 1.5Mbps. The measured spectrum, EVM and ACPR for π/8 D8PSK are shown in Figure 7 respectively. With -17.8dBm output, the EVM achieved is 7.5%, the ACPR is -26dBc, and PSD is more than -20dBr. Due to the relaxed ACPR, the total power consumption can be decreased to 1.58mW, as compared to the 15.6 mode.

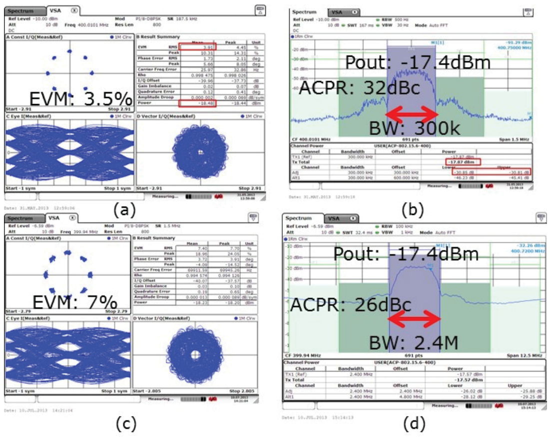

Figure 7 TX measurement: (a,b) D8PSK@187.5k symbol rate; (c,d)D8PSK @1.5M symbol rate

3.2 Receiver Evaluation

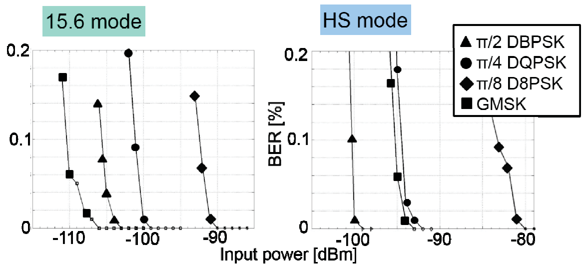

Figure 8 BER based sensitivity measurement in different modes

The sensitivity of the receiver is evaluated based on bit-error-test and the threshold hold value is set to 0.1%. The measurement is repeated for different modes in MICS and ISM bands. The BER plot is as shown in Figure 8. The adjacent-channel-rejection (ACR) is also measured based on BER measurement and the results meet the 15.6 specifications.

3.3 System Evaluation

As in Figure 9, the complete system, including the transciever, the FPAG based DBB, MCU to control the transceiver, is evaluated with the body fluid body, showing an effective 1-meter link around the human body.

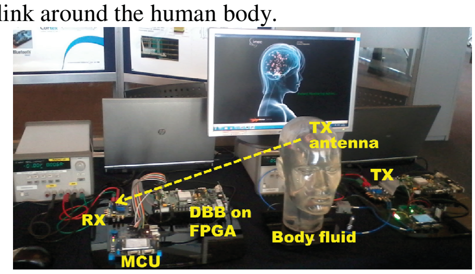

Figure 9 system evaluation setup

4. CONCLUSIONS

A first MICS/ISM-band 802.15.6 standard-compliant transceiver is reported for medical application. As compared to other standard compliant prior arts [6, 7] and products, our work supports variable data range from 11kbps to 4.5Mbps and consumes 5X~10X lower power. The transmitter power consumption is 2.22mW, including simulated 0.5mW from TX DBB. The receiver is programmable in terms of noise performance and power consumption for different application scenarios, resulting 1.9mW for noise-figure-optimized mode and 2.2mW for power-efficient mode, assuming 0.7mW from RX DBB.

Table 3 Performance summary and comparison

		AD ADF7021-V	Nordic nRF9E5	TI CC1101	[6]	[7]	This work		
Modulation		4-FSK MSK	GFSK	4-FSK OOK	FSK	FSK OOK	π/2 DBPSK	GMSK	π/8 D8PSK
DR[kb/s]		24	100	600	800	100	11	187.5	4500
Tech.		-	-	-	CMOS 0.18	CMOS 0.18	CMOS 0.04		
TX	P_{DC} [mW]	31	21	23	11	27	2.28	2.27	2.28
	Pout [dBm]	0	-10	-6	-4.5	10	-17	-10	-17
RX	P_{DC} [mW]	42	23	30	11	2.1	1.9	2.2	2.2
	Psens [dBm]	-114	-100	-95	-83	-111	-112	-110	-83

5. REFERENCES

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