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Wireless Wire-the 60 GHz Ultra-Low Power Radio System

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Abstract — This article presents basic issues regarding design and development of a 60 GHz ultra-low power radio system for Ambient Intelligence (AmI) applications. It demonstrates the validity of choosing the 60 GHz frequency band to design low power radios by a mathematical model, and proposes an overview of a cross-layer optimization flow to minimize power dissipation. Moreover, a completed RF front-end architecture, i.e. the transmitter and the receiver, is simulated according to the proposed methodology. Crucial concerns, challenges and solutions are discussed based on it. Simulation results are given, which verify the theoretical conclusions of 120 pJ/bit power consumption.

Index Terms — 60 GHz, E_{bit} , Ultra-Low Power, CMOS, Beamsteering, Wake-up Radio.

I. INTRODUCTION

With rapid convergence and development of computing technologies, wireless communications and sensing technologies, ubiquitous and self-contained wireless systems in homes or companies begin to play an important role in progress of the fourth-generation (4G) wireless technologies. These “smart” wireless systems should be invisible, low cost and most of all, power efficient enough to accommodate people’s daily lives without any interruptions, especially in an AmI applications scenario. Above that, an “all-in-one” solution is expected in order to replace many wireless standards, e.g. BluetoothTM, Wireless Local Networks (WLAN), Wireless Personal Networks (WPAN) etc., by a unique system, which is faster than conventional wireless short-range radio but as reliable as a cable-based transmission system.

The 60 GHz frequency band has been drawing a lot of attention due to its attractive features such as multiple gigahertz unlicensed spectrum, small electronics feature size, inherent suitability to directional antennas, high security and high frequency reuse factor. On the other hand, this frequency band is also used to be disregarded by low-power system designer due to the following reasons: (1) high transmission pathloss; (2) technology limitations, e.g. low gain, insufficient cut-off frequency; (3) high noise, which in turn increase peak power consumption dramatically compared to lower frequency systems like ZigBeeTM or IR-UWB; (4) inaccurate modeling; (5) lack of a mature design methodology. However, high frequency bands may offer an opportunity for decreasing the average

power consumption, which can be properly measured by an Equivalent-Figure-of-Merit (EFOM), energy-per-bit (E_{bit}). A relevant example is the 17 GHz low duty-cycle radio project conducted by Philips Research Eindhoven in 2007, which has achieved 1.75 nJ/bit for both transmitter and receiver front-end [1]. By taking advantages of 60 GHz and adding other advanced techniques, bottlenecks that exist in the 17 GHz system, like LO accuracy, data rate limitation and turn-on time (of the duty-cycled radio) are expected to be mitigated and E_{bit} to be significantly decreased.

The system models, design methodology and architecture are discussed and verified at section I, II III and IV. Simulation results and conclusions are given based on all these theories and models in section V and VI.

II. ANALYSIS OF FRONT-END ENERGY MODEL

E_{bit} is defined as system energy consumption over total number of bits to be transmitted or received, where energy consumption E_{tot} is a product of power consumption P_{tot} and communication time t_{tot} , and total bits number N is a product of data rate R and communication time. Thus, E_{bit} can be written as E_{tot}/N or P_{tot}/R .

A system energy model will be derived below to explore the relationship between E_{bit} , operation frequency, transmission data rate and other circuit-level parameters.

A. Transceiver Power Profiles

Generally speaking, an Ultra-Low Power (ULP) wireless system may have two operation modes: always-on and duty-cycled activation, including periodical listening and radio-triggered wake-up, shown in Fig. 1. Always-on radios have to be extremely low power all the time in order to achieve low total energy consumption and long battery life, and are limited to low frequency and low data rate applications, e.g. medical sensors, RFID, and so on. Thus, it might not be a promising candidate for the AmI scenario, which normally requires decent throughput and fast communication speed. More and more research has been focusing on the second category, namely, the duty-cycled radios.

Within the duty-cycled radios category, the radio-triggered receiver is particularly interesting because of its

highly efficient power management nature. In other words, by removing periodical listening activity of receiver, the total power will be used for communication only. Several techniques like zero-biased diode detection, MEMS based detection and electronic circuit detection are being investigated recently.

Fig. 1 Power profiles in one average duty-cycle.

Further, it is found by definition that E_{bit} might be decreased by increasing the data rate, as long as we can keep P_{tot} within a reasonable range, namely, not increase proportionally with R . A possible solution for this will be described in the following sections.

B. Power Efficiency

In order to investigate determining factors of P_{tot} mathematically, first the circuit efficiency will be analyzed. It can be easily found that the efficiency of a class A to C power amplifier (PA) can be expressed as [2]

$$\eta = \frac{\frac{1}{2} \cdot i_{fund}^2 \cdot R_{opt}}{I_{DC} \cdot V_{supply}} = \frac{\frac{1}{2} \cdot \left[\frac{I_{PK}}{2\pi} (\alpha - \sin \alpha) \right]^2 \cdot \frac{V_{breakdown}}{I_{PK} + I_{bias}}}{\left[\frac{I_{PK}}{\pi} \left(\sin \frac{\alpha}{2} - \frac{\alpha}{2} \cos \frac{\alpha}{2} \right) \right] \cdot V_{supply}} \quad (1)$$

where i_{fund} is the amplitude of current with fundamental frequency at the output, R_{opt} is the optimized load impedance, I_{DC} is total current consumption, V_{supply} is the supply voltage, I_{PK} is the peaking AC current, I_{bias} is the DC biasing current, $V_{breakdown}$ is the breakdown voltage and α is the PA conduction angle.

If we simplify this complex equation and substitute relevant items with circuit-related parameters, it becomes

$$\eta = \frac{(\alpha - \sin \alpha)^2 \cdot V_{breakdown}}{8\pi \cdot \left(\sin \frac{\alpha}{2} - \frac{\alpha}{2} \cos \frac{\alpha}{2} \right) \cdot V_{supply}} \cdot \frac{1}{1 + \frac{I_{bias} \cdot j\omega}{I_{in} \cdot \omega_T}} \quad (2)$$

where I_{in} is the input AC current amplitude, ω_T is the cut-off angular frequency and ω is the operation frequency.

Thus, it can be concluded that the PA efficiency is inversely proportional to ω , or $\eta = A / (1 + B \omega^{-1})$, where A and B are constants only decided by the circuit-level parameters in the equation and stay the same if all others are unchanged.

The total transmitter efficiency can be approximately modeled as the PA efficiency when total power consumption is dominated by the PA, which is the case in the “pulsed-shape” power profile in Fig. 1.

C. Front-End Energy Model

Receiver system noise factor (F) can be modeled as [3]

$$F = 1 + \left(\frac{\omega}{2\pi \cdot 6 \cdot 10^9} \right) \propto \omega \quad (3)$$

which is approximately proportional to frequency.

Furthermore, according to Frii's equation, pathloss (PL) in the free space (Line-of-sight assumption) can be expressed as

$$PL = \left(\frac{4\pi d}{\lambda} \right)^2 = \left(\frac{2d\omega}{c} \right)^2 \propto \omega^2 \quad (4)$$

where λ is wavelength, c is speed of light and d is distance.

System sensitivity (S) is a product of total noise floor, noise factor and minimum signal-to-noise ratio (SNR), i.e. $KTB F SNR_{min}$, or $KTB F (E_b R/N_0 B)$, where B is the bandwidth, R is the data rate and E_b/N_0 is the SNR per bit.

Thus, the minimum output power of the transmitter becomes

$$P_{out} = \frac{S \cdot PL}{G_{tx} \cdot G_{rx}} = \frac{(A_{MDS} \omega + B_{MDS}) \cdot R \cdot \left(\frac{2d\omega}{c} \right)^2}{G_{tx} \cdot G_{rx}} \quad (5)$$

or

$$P_{out} = \frac{(A_{out} \omega^3 + B_{out} \omega^2) \cdot R}{G_{tx} \cdot G_{rx}} \quad (6)$$

where G_{tx} and G_{rx} is the antenna gain of the transmitter and receiver, respectively.

So, the front-end power consumption P_{DC} can be modeled as the summation of transmitter power P_{out} , receiver power P_{RX} and turn-on power $P_{turn-on}$, or

$$P_{DC} = \frac{(A_{out} \omega^3 + B_{out} \omega^2 + C_{out} \omega + D_{out} \omega + E_{out}) \cdot R}{G_{tx} \cdot G_{rx}} + P_{RX} + P_{turn-on} \quad (7)$$

The leakage power during sleeping is eliminated by powering down the whole front-end with additional power gating transistors, so it is neglected in this derivation [4].

The antenna gain is the product of the radiation efficiency η_{rad} and the antenna directivity D ($4\pi A/\lambda^2$ for a normal aperture antennas, where A is antenna area). By substituting these into (7), the total power consumption becomes

$$P_{DC} = \frac{(A_{DC} + B_{DC}\omega^{-1} + C_{DC}\omega^{-2} + D_{DC}\omega^{-3} + E_{DC}) \cdot R}{\eta_{tot,tx} \frac{4\pi A_{tx}}{c^2} \cdot \eta_{tot,rx} \frac{4\pi A_{rx}}{c^2}} + P_{RX} + P_{turn-on} \quad (8)$$

Thus, E_{bit} becomes

$$E_{bit} = \frac{A_{DC} + B_{DC}\omega^{-1} + C_{DC}\omega^{-2} + D_{DC}\omega^{-3} + E_{DC}}{\eta_{tot,tx} \frac{4\pi A_{tx}}{c^2} \cdot \eta_{tot,rx} \frac{4\pi A_{rx}}{c^2}} + \frac{P_{RX} + P_{turn-on}}{R} \quad (9)$$

These derivations show that a transmitter system at higher frequencies, e.g. 60 GHz, may achieve lower energy per bit if the antenna is directional and highly efficient assuming the same antenna area! The result will be somehow limited by technology, receiver power and turn-on power, which do not scale linearly with frequency or other parameters. However, a high data rate transmission, which can only be achieved at a high frequency band, and fast turn-on techniques will be the promising solution regarding these issues.

D. Beamsteering

Further, if we replace the normal directional antenna with an n -element antenna array and perform beamsteering technique based on it, the total antenna gain of the signal will be improved by a factor of n^2 , and the system SNR will be improved by a factor of n . This technique offers us a highly efficient way to compensate high pathloss and improve the system sensitivity accordingly. One thing should be carefully investigated is the trade-off between the spatial resolution and the total power dissipation.

III. SYSTEM CONSIDERATIONS AND ARCHITECTURES

A real ULP system can only be achieved by cross-layer e.g. networking, medium-access and physical layers, co-design and optimization. Ad-hoc networking and multi-hop routing are chosen to achieve most flexible communication link and alleviate the power burden of each nodes. In this way, the communication coverage range is improved, and a global optimization will be achieved on the entire network, which makes this new low-power solution feasible in practice.

A 60 GHz transmitter is shown in Fig. 2. A 4-path phase array is used to optimize the system efficiency. The local oscillator (LO) is a co-planar waveguide (CPW) transmission line based negative resistance oscillator, which offers 0 dBm power, low phase noise 60 GHz carrier signal to the phase shifter. In this case, the phase-locked-loop (PLL) is not required anymore because of the 7-GHz-wide bandwidth that relaxes the frequency accuracy requirement, and thus the turn-on power can be significantly reduced. Power loss through a 4-bit 60 GHz phase shifter is presented in [5] as 5 dB, and 5 dB power gain can be obtained from each power amplifier (PA),

which is a feasible performance with deep sub-micron CMOS technology, e.g. CMOS 90 nm or CMOS 65 nm. With 4 paths beamsteering, 0 dBm output power is obtained in each path, and 12 dBm power can be realized in total, which is sufficient for this AmI applications.

A 1-Gbps data rate is chosen according to the applications scenario. Since the bandwidth efficiency requirement is relaxed in this case, a simple On-Off-Keying (OOK) modulation scheme is applied to switch the biasing of PAs which can be saturated for high efficiency. This configuration offers an optimized overall low power state by minimizing the linearity and demodulation SNR requirements and allowing the use of nonlinear high-efficiency modules. In addition, the transmitter and receiver circuits are simplified to the maximum extent.

Fig. 2 60 GHz PLL-less 4-path Beamsteering Tx.

The receiver architecture is shown in Fig. 3. Radio-triggered wake-up module is implemented based on an injection-locked wake-up stage, which offers high capturing sensitivity as well as minimum stand-by power. In addition, wireless charging is realized with a high power pulse through the charging path to a rechargeable battery.

Fig. 3 60 GHz Self-Demodulation 4-path Beamsteering Rx.

As a result of beamsteering, the front-end gain requirement is maximally reduced by 12 dB with 4-path antenna array. The system sensitivity requirement is calculated as about -62 dBm at 60 GHz band with 7 GHz bandwidth. The Rx front-end power gain is at least 5 dB in order to achieve 10^{-3} Bit-Error-Rate (BER) with OOK modulation. Further, if we assume in the worst case, an adjacent undesired transmitter injects a -48 dBm (12 dBm maximum output power with 0.2 m minimum communication range) interference signal to our receiver, the resulting IIP3 requirement is about -38 dBm, which is, fortunately, quite relaxed. Besides, the system noise figure can be estimated by (3) to be at a level of 11 dB.

IV. SIMULATION RESULTS

According to [6], an EFOM called power linearity factor can be used to trade-off power consumption, gain and linearity of each individual circuit block, which is

$$\kappa = \frac{P_{DC}}{\text{Gain} \cdot \text{IIP3}} \quad (10)$$

Minimum power dissipation can be estimated based on benchmarks of this EFOM. Thus, gain and IIP3 distributions of each individual block towards minimum power dissipation can be estimated as follows:

TABLE I
Specifications of Receiver Building Blocks

	Gain (dB)	NF (dB)	IIP3 (dBm)
Antenna Array	12 (max.)	-	-
LNA	15	6	-30
Phase Shifter	-5	-	-
Mixer	-7	15	-22.4
LPF	-2	-	-

The total receiver power gain is 13 dB and peak power dissipation is about 120 mW. A 6-dB margin of gain is left to counter the interference with -60 dBm power. The simulated time domain input and output signals are shown in Fig. 4.

Fig. 4 Input and Output Signals of the Transmitter.

V. CONCLUSIONS

This 60 GHz 4-path beamsteering front-end is estimated to consume 120 mW peaking power to achieve 10^{-3} BER. With 1-Gbps data and OOK modulation, the system E_{bit} is about 120 pJ/bit, which is, to the author's knowledge, the minimum value in current ULP research state. By using a supercapacitor, i.e. an electrochemical capacitor that has very high energy density, the high power peak is smoothed to an ultra-low level, and tens of years of battery life is possibly to be achieved by a 1.5 V Alkaline battery.

Fig. 5 Comparison of E_{bit} with different data rates.

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REFERENCES

- [1] Wanghua Wu, Mihai Sanduleanu, Xia Li, John Long, "17GHz RF Front-Ends for Low-Power Wireless Sensor Networks," in *Proc. 2007 IEEE Bipolar/BiCMOS Circuits and Technology Meeting*, US, pp. 164-167.
- [2] Steve C. Cripps, *RF Power Amplifiers for Wireless Communications*, Norwood MA: Artech House, 2006.
- [3] Thomas H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits, Second Edition*, UK: Cambridge, 2003.
- [4] Barry Pangrle, Shekhar Kapoor, *Leakage Power at 90nm and Below*, Tutorial of Synopsys Inc., 2005.
- [5] Yu, Y., Baltus, P.G.M., Smulder, P.F.M., "Systems and Architectures for very High Frequency Radio Links," in *Proc. 2007 IEEE Advances in Analogue Circuit Design Workshop*, Ostend, Belgium, pp. 237-258.
- [6] Peter Baltus, *Minimum Power Design of RF Front Ends*, Ph.D dissertation: Eindhoven University of Technology, the Netherlands, 2004.