60 GHz Ultra-Low Power Radio

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Abstract **—This paper presents the system level considerations and analysis of an ultra-low power Radio-Frequency (RF) front-end. A completed mathematical model is derived based on system, circuit and technology parameters to prove the validity of choosing high frequency bands with gigabits per second data rate and simple modulation scheme, e.g. 60 GHz with 1-Gbps data rate and On-Off Keying (OOK) modulation to achieve ultra-low energy per bit. Beamsteering technique is proposed to achieve the minimum power optimization and improve the communication quality, too.**

Index Terms **— 60 GHz, E_{bit}, Ultra-Low Power, OOK, Beamsteering.**

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. BlueTooth^{TM}, 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 ZigBee^{TM} 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.

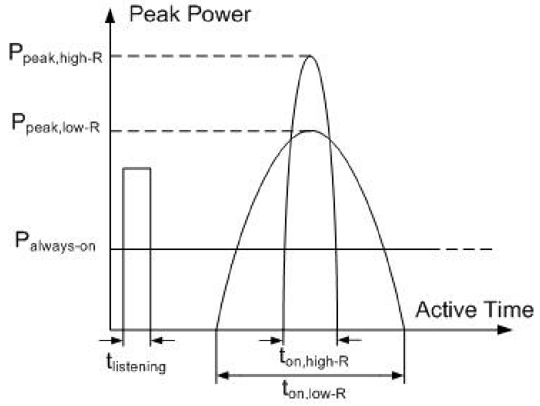

Fig. 1 Power profiles in one average duty-cycle.

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 η of a class A to C power amplifier (PA) can be expressed as [2]

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

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

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

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 $\eta=A_\eta/(1+B_\eta\omega^{-1})$, where A_η and B_η 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]

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

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

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

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. $KTB\cdot F\cdot SNR_{min}$, or $KTB\cdot F\cdot(E_b\cdot R/N_0\cdot B)$, 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

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

or

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

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}/η, receiver power P_{RX} and turn-on power $P_{turn\text{-}on}$, or

$$P_{DC} = \frac{(A_0\omega^4+B_0\omega^3+C_0\omega^2+D_0\omega+E_0)\cdot R}{G_{tx}\cdot G_{rx}} + P_{RX} + P_{turn-on} \qquad (7)$$

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

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

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.

E. Optimized Data Rate

In this section, the optimized data rate will be derived towards minimum power consumption of the system.

The system *SNR* of the receiver, i.e. SNR_r, is defined as the receiving power over the system noise floor, or P_r/KTB, and P_r is $P_{out}\cdot G_{tx}\cdot G_{rx}/PL$. So, the SNR at the input of the demodulator, i.e. SNR_{dem}, can be written as

$$SNR_{dem} = \frac{SNR_r}{F} = \frac{P_{out}\cdot G_{tx}\cdot G_{rx}}{PL\cdot F} \quad (10)$$

From the Shannon-Hartley theorem, the channel capacity is

$$C = R\cdot\varepsilon = B\log_2(1 + SNR_{dem}) \quad (11)$$

where $\varepsilon \geq 1$ and is a pure number.

So, SNR_{dem} becomes

$$SNR_{dem} = 2^{\frac{\varepsilon\cdot R}{B}} - 1 = \frac{P_{out}\cdot G_{tx}\cdot G_{rx}}{KTB\cdot PL\cdot F} \quad (12)$$

or

$$P_{out} = \frac{KTB\cdot PL\cdot F(2^{\frac{\varepsilon\cdot R}{B}} - 1)}{G_{tx}\cdot G_{rx}} \quad (13)$$

The power consumption of the transmitter can be divided into two parts: the power of the PA, i.e. P_{out}/η and the Local Oscillator (LO), i.e. P_{LO}. The transmitting and receiving time, i.e. T_{tx} and T_{rx}, respectively, are defined as the package length (*L*) over the data rate. Thus, the total power consumption Ptot can be written as

$$\begin{aligned} P_{tot} = {} & [(\frac{P_{out}}{\eta} + P_{LO})\cdot T_{tx} + (P_{rx} + P_{LO})\cdot T_{rx} \\ & + P_{switch}\cdot T_{switch} + P_{wakeup}\cdot T_{wakeup} \quad (14) \\ & + P_{idle}\cdot(T - T_{tx} - T_{rx} - T_{switch} - T_{wakeup})]\cdot\frac{1}{T} \end{aligned}$$

where P_{rx}, P_{switch}, P_{wakeup} and P_{idle} are the receiver, switching, wake-up and idle power consumptions, respectively, whilst T_{switch}, T_{wakeup} T_{idle} and *T* are the switching, wake-up idle and total communicating time, respectively.

Assume the switching, wake-up and idle power are design constants (circuit dependent only), the question becomes finding the minimum of first two items. Let $\partial P_{tot}/\partial_R$=0, or

$$\frac{\partial}{\partial R}\{[\frac{KTB\cdot\alpha\cdot F(2^{\frac{\varepsilon\cdot R}{B}} - 1)}{G_{tx}\cdot G_{rx}\cdot\eta} + 2P_{LO} + P_{rx} - 2P_{idle}]\cdot\frac{L}{R\cdot T}\} = 0 \quad (15)$$

we will get

$$R = 1 + \frac{2P_{LO} + P_{rx}}{\frac{KT\cdot PL\cdot F\cdot\varepsilon\cdot 2^{\frac{\varepsilon\cdot R}{B}}}{G_{tx}\cdot G_{rx}\cdot\eta}} \quad (16)$$

Let's assume ε equals 1, T is 293 K, *PL* is $1.58\cdot 10^8$ at 60 GHz within 5-m's range, F is 12.6, antenna gain is 0 dBi in the worst case and PA efficiency is 5% based on the present technology limitations. The power consumption of the LO and the receiver is a constant called P_c. The equation becomes

$$R - 1 = \frac{P_C\cdot 1\cdot 0.05}{1.38\cdot 10^{-23}\cdot 293\cdot 1.58\cdot 10^8\cdot 12.6}\cdot 2^{\frac{B}{R}} \quad (17)$$

R is a function of P_C, electronics efficiency, signal bandwidth and working temperature (noise figure and pathloss are taken as prerequisites, which have been evaluated by link budget analysis). Assume P_C is 100 mW, temperature is 80 centigrade and 3-dB signal bandwidth is 2 GHz (system bandwidth is 7 GHz), the optimized data rate can be plotted as

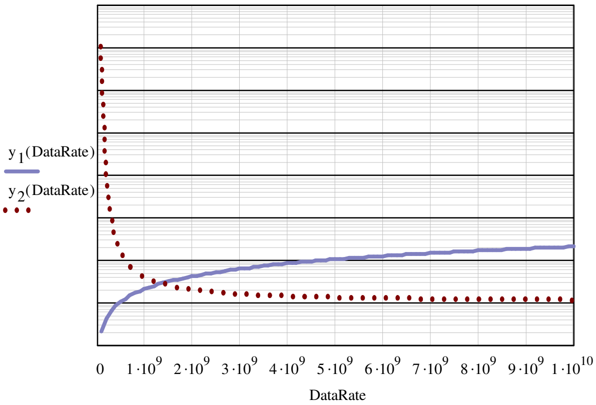

Fig. 2 Optimized data rate.

It shows a range from 1 Gbps to 2 Gbps, which will lead to an overall optimization state and minimum power consumption accordingly.

F. Modulation Scheme

Modulation scheme also plays a critical role in a low power system. Normally, it is a trade-off between bandwidth efficiency and energy efficiency, and the energy efficiency is always considered as the SNR per bit, i.e. E_b/N_0 for system level designs. However, when considering electronics efficiency, it may be a different story [4].

From (5), the further derivation shows

$$(P_{tx}+P_{rx})\cdot\eta = (KTB\cdot F\cdot\frac{E_b}{N_0}\cdot\frac{R}{B})\cdot\frac{PL}{G_{tx}\cdot G_{rx}} \tag{18}$$

So the total power consumption becomes

$$P_{tot}=P_{tx}+P_{rx}=\frac{(KTB)\cdot F\cdot(\frac{E_b}{N_0}\cdot\frac{R}{B})\cdot PL}{\eta\cdot G_{tx}\cdot G_{rx}}=\frac{KT\cdot F\cdot(\frac{E_b}{N_0})\cdot R\cdot PL}{\eta\cdot G_{tx}\cdot G_{rx}} \tag{19}$$

The noise factor is limited by frequency bands as (3) shows. *R*, *PL* and antenna gain is fixed values for a particular system. Thus, the EFOM shall be defined as the energy efficiency over the electronics efficiency, i.e.

$$EFOM=\frac{\frac{E_b}{N_0}}{\eta} \tag{20}$$

Lower EROM indicates better energy efficiency. If we use this EFOM to compare some modulation schemes that are frequently used in present low-power systems, the following figure will be obtained

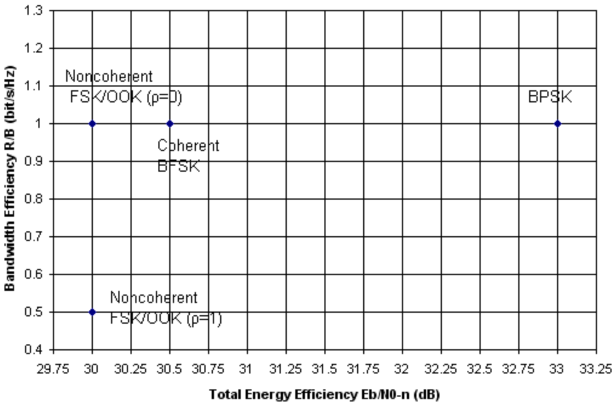

Fig. 3 Comparison of the modulation schemes.

Since the bandwidth efficiency requirement at higher frequency bands, e.g. 60 GHz is not critical, the modulation scheme should be chosen that leads to minimum power or highest energy efficiency. It can be conclude that the non-coherent OOK or FSK modulations are proper choices due to their low EFOM. Thus, the simple OOK modulation is chosen in this low-power RF system.

G. Beamsteering

In order to maximize the antenna gain as well as the *SNR*, 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. It has been proved that 4-path beamsteering is a good trade-off between the spatial resolution and the total power dissipation [5].

III. CONCLUSIONS

This 60 GHz ultra-low power beamsteering front-end is analyzed in this paper. From the data of state-of-the-art equivalent systems, the estimated power consumption is 120 mW in order 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.

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