An EFOM for cross-layer optimization towards low-power and high-performance wireless networks

An EFOM for Cross-Layer Optimization towards Low-Power and High-Performance Wireless Networks

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Abstract—**This paper presents an Equivalent-Figure-of-Merit (EFOM) for designing and evaluating a wireless system towards low power and high performance. Relevant factors like delay, minimum latency, overhead length of a package, package length, data rate, bit-error-rate (BER), pre-receiving time of the receiver, average duty cycle and electronics performance factor are synthesized within a unique model. Comparing to other FOMs like energy per bit E_{bit}, this EFOM is able to rank the overall performance of a wireless network concerning the information not only power efficiency but also about communication quality (speed, BER, wake-up time, etc.), communication effectiveness and user's satisfaction. Applying this model to the system design, a 60 GHz self-demodulating receiver is designed and optimized, which obtains high-speed versatile performance in a low-traffic wireless network with better power efficiency comparing to other low-power wireless interface, e.g. Bluetooth and so on.**

Key Words—**EFOM, Cross-layer, 60 GHz, Self-demodulating.**

I. INTRODUCTION

Wireless electronic devices become quite indispensible in one's daily life. For example, people may enjoy watching movies from a laptop or music from the mp3 players. Moreover, these devices can be connected with each other via a wireless link, e.g. the Bluetooth interface, in which complicated wires and cables are eliminated. Consequently, the data loading process becomes much more convenient and limitless with the environment. However, the extra power consumed by such a wireless interface turns out to be very critical. As always heard, "turn off the Bluetooth when one do not really need it, otherwise the battery will go empty soon". The situation is even worse when these wireless connections are used frequently and people will have to re-charge the batteries of these mobile devices several times per week. In a room, several wireless nodes may form into a wireless network, and the data is shared, relayed and transferred within it. In order to maximize the effective working time of this network, the power consumption of the network should be minimized while on the other hand the communication quality should also be guaranteed.
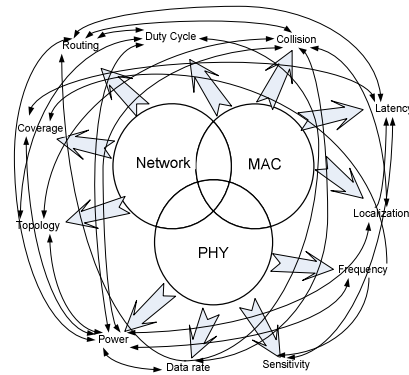
Fig. 1 Cross-layer parameters of a wireless system.

Low power performance is not a straightforward task. A low power in the PHY layer would mean that the burden is shifted to the MAC or other layers. In other words, one may need a much more complicated protocol to transfer the data among some ultra-simple "non-smart" physical nodes. The overall power consumption is not necessarily optimized. Therefore, the cross-layer optimization on the power consumption becomes important and useful. Unfortunately, there are too many changeable parameters for each layer and they are more or less dependant on each other, which makes the optimization unobvious and indirect, as shown in Fig. 1. As a result, a cross-layer EFOM is crucial to indicate the direction for the optimization as well as to evaluate the effectiveness of it.

In Section II, an EFOM is proposed for the cross-layer optimization. In Section III, applications of the EFOM and the self-demodulating receiver architecture is discussed accordingly and the comparison of this work and other equivalent low-power systems is given afterwards. The final conclusions are drawn in Section IV

II. EFOM

Based on the above discussion, the cross-layer EFOM is derived and analyzed in this section. The power-related key

parameters of the PHY, MAC and network layers are presented and their relationships are discussed.

A. Key parameters of different layers

The total delay of a single node in a wireless network can be expressed as

$$\tau_{tot} = \tau_{Propagation} + \tau_{Serialization} + \tau_{Queuing} + \tau_{Processing} \quad (1)$$

where $\tau_{Propagation}$ is the propagation delay, defined by distance over wave propagation speed; $\tau_{Serialization}$ is the serialization delay, which is defined as the time of starting to ending of reception; $\tau_{Queuing}$ is the time consumed by waiting for forwarding, and $\tau_{Processing}$ is the time for intermitting nodes to processing the package.

When a network is established with a certain carrier frequency, communication distance, and package forwarding mechanism, the total delay τ_{tot} can be re-written as

$$\tau_{tot} = \tau_C + \tau_{Serialization} \quad (2)$$

where τ_C is the minimum latency, or the summation of propagation, queuing and processing delays, which can be taken as a constant for a certain type of networking configuration, and $\tau_{Serialization}$ can be calculated by the receiver (Rx) overhead $t_{Rx,overhead}$ plus the package length L over the data rate R, i.e.

$$\tau_{tot} = \tau_C + t_{Rx,overhead} + L/R \quad (3)$$

From the previous research [1], it is known that data rate is sub-linear to the power consumption of a front-end circuit as

$$P_{DC} = P_{pr} + P_{Rx} + k \cdot R \quad (4)$$

where P_{DC} is the total DC power consumption of a node, P_{pr} is the power consumption of a receiver (Rx) for pre-receiving activities (e.g. listening, synchronization or settling the Rx), P_{Rx} is the Rx power consumption, which has no direct relation with R, and k is the electronics factor, which implies the circuit performance of the front-end.

Solving for R from (3), we obtain

$$R = \frac{L}{\tau_{tot} - \tau_C - t_{Rx,overhead}} \quad (5)$$

Substituting (5) into (4), the P_{DC} can be expressed as

$$P_{DC} = \frac{L \cdot k}{\tau_{tot} - \tau_C - t_{Rx,overhead}} + P_{pr} + P_{Rx} \quad (6)$$

According to the definition of the energy per bit (E_{bit}), the system energy efficiency can be evaluated by the power consumption over the data rate. It is a fair FOM to evaluate the energy efficiency of an always-on communication system. However, some important information is missing in this FOM, e.g. the type of the device operation (duty-cycled or always-on) and the quality of the communication (the BER). Consequently, it does not directly indicate the level of the system average power consumption, which is the parameter determining the battery life. Therefore we define another FOM average energy per bit of correctly received bits ($E_{ave,corr}$) as

$$E_{ave,corr} = \frac{P_{DC}}{R_{effect}} \cdot \frac{t_{on}}{t_{tot}} \quad (7)$$

where R_{effect} is the effective data rate, which is calculated by the data rate times (1-BER), t_{on} is the on time and the t_{tot} is the total observing time.

Substituting (6) into (7), the EFOM can be expressed as

$$EFOM = -10 \cdot \log(\frac{\frac{L \cdot k}{\tau_{tot} - \tau_C - t_{Rx,overhead}} + P_{pr} + P_{Rx}}{R_{effect}} \cdot \frac{t_{on}}{t_{tot}}) \quad (8)$$

$$(\tau_{tot} \le \tau_{max})$$

where τ_{max} is the maximum user-happy delay, which can be obtained from the quality-of-experience (QoE) experiments.

The coefficient k can be calculated as following: from [2], it is known that the system noise factor increases sub-linearly with frequency in certain technology when the system architecture is similar. Taking [3] as the benchmark of deep submicron CMOS, the receiver noise factor is estimated as

$$F = 1 + (\frac{\omega}{5 \cdot 10^9}) \quad (9)$$

where ω is the frequency and $5 \cdot 10^9$ is the technology- and architecture-correlated factor.

The pathloss PL is calculated by

$$PL = (\frac{4\pi d}{\lambda})^2 = (\frac{2d\omega}{c})^2 \quad (10)$$

where d is the communication distance, λ is the carrier wave length and c is the speed of light.

The receiver sensitivity S can be calculated as

$$S = KTB \cdot F \cdot \frac{E_b}{N_0} \cdot \frac{R}{B} \quad (11)$$

where K is the Boltzmann's constant, T is the temperature in Kelvin, E_b/N_0 is the signal-to-noise-ratio per bit, and B is the bandwidth. The maximum output power P_{out} of the transmitter (Tx) can be estimated by

$$P_{out} = \frac{S \cdot PL}{G_{tx} \cdot G_{rx}} = \frac{KTB \cdot (1 + \frac{\omega}{5 \cdot 10^9}) \cdot (\frac{E_b}{N_0} \cdot \frac{R}{B}) \cdot (\frac{2d\omega}{c})^2}{G_{tx} \cdot G_{rx}} \quad (12)$$

where PL is the path-loss and G_{tx}, G_{rx} are the antenna gains of the Tx and Rx, respectively.

The power consumption of the Tx is calculated as output power over electronics efficiency η, which is preferably decided by the power amplifier (PA). Comparing (4) and (12), the expression of k can be obtained.

$$k \approx \frac{KT \cdot \frac{E_b}{N_0} \cdot (\frac{2d}{c})^2}{G_{tx} \cdot G_{rx} \cdot \eta \cdot 2\pi \cdot 5 \cdot 10^9} \quad (13)$$

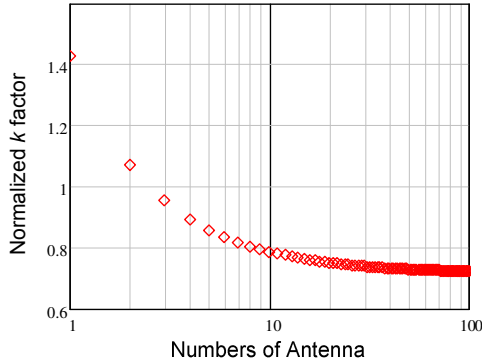where smaller k would indicate more efficient PHY system.

Fig. 2 Antenna number vs. *k* factor.

Fig. 3 A self-demodulating receiver.

B.   Further discussion

From (13), it can be seen that the electronics factor *k* is a good FOM to evaluate the PHY-layer performance. Overall speaking, comparing (12) and (13), smaller *k* means lower Tx power consumption at the same data rate and with same output power of the Tx. To improve *k*, some techniques are investigated. For example, using *n*-path phase array beamsteering technique can introduce an extra power gain from antenna as *20·$\log_{10}n$* dB (or *10·$\log_{10}n$* dB if single local oscillator (LO) is used). Since the power gain is generated by the antenna (gain of the equivalent isotropically radiated power, or EIRP) instead of the drivers or PA, the total power consumption is decreasing almost linearly with the same total output power. In other words, the electronics efficiency is improved by *2n/(n+1)* with LO is at the same power consumption level as the following stage in one path, as shown in Fig. 2.

Trade-offs and transforms among parameters can be found by the EFOM equation. For example, when the duty-cycle of a node becomes higher, or the ratio t_{on}/t_{tot} increases, in order to maintain a certain EFOM level, we should either need a better front-end circuit (decrease *k*), or reduce the pre-receiving time of the receiver, or increase the data rate at certain BER by improving the bandwidth efficiency. These methods can be treated (partially) orthogonal during system design, which simplifies the whole process.

Recalling (8), the following analyses can be made: for a better EFOM, (1) smaller τ_C is preferred, which in turn reflecting to the network configuration, means that the communication distance of the each node should be kept small and data forwarding time should be minimized. As a result, the self-configured ad hoc network with multi-hop routing would be a reasonable choice; (2) t_{on}/t_{tot}, $t_{Rx,overhead}$ and P_{pr} have to be minimized, which implies that in the MAC layer, the duty-cycle should be sufficiently low and the settling of the nodes should be fast, especially for short packages. A PLL-less receiver would be a realistic choice for saving of the start-up time; (3) in the PHY layer, R_{effect} should be increased and *k* has to be decreased. High data rate can be realized in a wide band system, e.g. in the 60 GHz ISM band, which offers 7 GHz license-free spectrum to support several Gbps data rate. To decrease *k*, constant-envelope modulation scheme is preferred, because it des not require linear PA in the Tx so the
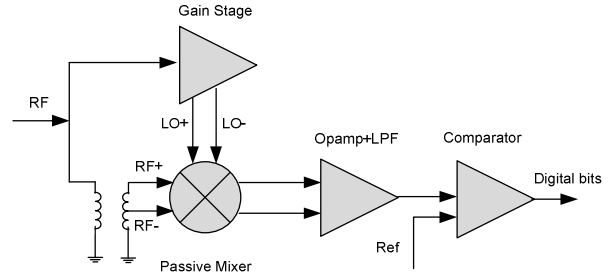
PA efficiency is improved and the signal can be simply demodulated by e.g. amplitude detector in the receiver side, which makes the circuits simple and thus low in power dissipation.

III.   EFOM APPLICATIONS

Based on the above discussion, a 60 GHz radio system is designed with its application targeting at medium to high data rate wireless personal-area network (WPAN). At this moment, the real-time communication or high-definition data streaming are not included, which, on the other hand, normally do not require a wireless link. Deep submicron CMOS technology, e.g. 65 nm CMOS with a unity-gain frequency f_T as up to 200 GHz, is used for the PHY circuitry design [4].

Referring to the parameters in EFOM, an overall optimization would be achieved in the following aspects. First of all, the radio should operate in a discontinuous mode to reduce the factor t_{on}/t_{tot} and so as the average power consumption. For the further minimizing of t_{on}/t_{tot} without missed alarms, a sophisticated MAC protocol is required. In [5], a duty-cycled wake-up scheme is proposed, which pushes the average "on" time of the main radio to the real minimum by using an extra very power-efficient duty-cycled wake-up radio for event detection. Besides, the nodes in the network work in a time-division multiple access (TDMA) mode so that the collision problem is not an issue. Due to the similar network features, e.g. node density, maximum distance and burst-mode transmission, this scheme is also suitable for the pre-receiving activities of our system.

In order to minimize P_{pr} and $t_{Rx,overhead}$ in the pre-receiving phase, e.g. in the switching-on or switch-off mode, a self-demodulating receiver is designed, as shown in Fig. 3. Comparing to the conventional voltage-controlled oscillator (VCO) with a phase-locked-loop (PLL) which normally would need 40 to 200 μs to be settled [6], the self-demodulation receiver only need less than maximally 3 μs to be settled, which is determined by the settling of high-gain stage, e.g. an injection-locked oscillator (IJLO) [7]. The incoming RF signal is divided into two paths. One is captured and amplified though the IJLO and then sent to a passive mixer as the driving voltage, and the other is sent to the mixer as the RF signal. In other words, the signal is down-converted by itself through the mixer to the DC baseband directly. The settling time of the receiver is then much shorter than a PLL because it does not require a low-frequency feedback loop and there is no frequency pulling behavior in an IJLO. The system sensitivity is further improved by using a frequency-sweeping
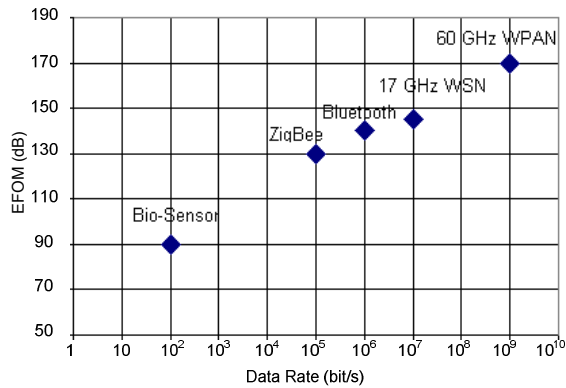
Fig. 4 The comparison of EFOM.

technique in the IJLO and the basic idea behind is to reduce the locking range of single-step locking action while still maintaining a 7 GHz locking range in total after sweeping the whole band. This operation has negative effect on the receiver pre-receiving time and increases the minimum latency due to the sweeping time. However, in the worst case, the total sweeping and locking time is below 10 μs, which is still better than a state-of-the-art PLL.

The data rate is chosen as 1 Gbps at 10^{-3} BER to support the applications like wireless point-to-point communication and video files transmission and so on. On-off-keying (OOK) modulation is used to reduce the system complexity as well as the power consumption [8]. However, since OOK modulation is vulnerable to interference and has a relatively poor E_b/N_0, the improvement of the k factor is not significant. Consequently, an n-path phase-array beamforming module is added to increase the antenna gain to combat the extra pathloss at high frequency and improve the k factor as discussed in Section II B. A phase shifter is inserted between the mixer and the gain stage. Combining n identical paths at the output of the mixer, the antenna gain is improved by $10 \cdot \log_{10} n$. The k factor and so as EFOM are improved too. In order not to increase additional complexity to train the pencil-beam antenna, an asymmetrical master node, e.g. an access point is needed to update the position information of the entire network to all the nodes, and the factor $t_{Rx,overhead}$ is minimized in such a way too.

EFOM can also be used to compare the overall performance of different wireless standards. Though some of these systems target at very different applications and have very different specifications, it would still be useful to evaluate them by the overall power efficiency and communication quality, which on the other hand, to some extent also indicates the overall design complexity. When the systems are used for the same applications, e.g. a Bluetooth WPAN and a 60 GHz WPAN, this comparison would become more fair and important. In Fig. 4, the EFOM's of biosensor, ZigBee radio, Bluetooth Radio, 17 GHz ULP and this work are compared, and it shows a linear increase of the system overall performance [9]. Qualitively speaking, the system power efficiency and communication quality is improved while the system throughput is also increased, which verifies our theory.

IV. CONCLUSION

This paper derives an EFOM for the design and optimization of a low-power, high-performance wireless system. This EFOM reveals some relationships and trade-offs of parameters on different layers, e.g. the relationship among the average duty-cycle, the latency, the overhead length of a package, the pre-receiving power, BER, the PHY parameters and user satisfaction delay. Based on the EFOM, a 60 GHz low-power self-demodulating receiver is proposed, which removes the slow turn-on PLL module while using the RF signal to down-convert itself. In this way, a normal settling time as hundreds to thousands of μs is eliminated and this is very efficient in power saving for a burst-mode operation system. Finally, different prevalent low-power communication systems like Bluetooth, ZigBee or 17 GHz WSN and UWB WPAN are compared with this 60 GHz WPAN system based on the EFOM. It is found that for short-range WPAN communications, the overall performance of ZigBee or Bluetooth are low, and the 60 GHz low-power system is much more power-efficient and has high performance at the highest data rate, i.e. in a level of several Gbps, so it would be a promising future direction for the next generation of high-speed and low-power WPANs.

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