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다수의 블루투스 피코넷 공존시의 상호 간섭에 대한 해석

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Analysis of Mutual Interference between Independent Bluetooth Piconets

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Abstract - Bluetooth can form many piconets within the same location. This network topology can cause mutual interferences, and the effect of interference is critical when a lot of Bluetooth networks coexist. In this paper, the performances of Bluetooth networks under mutual interference is analyzed and simulated using the concept of bit error rate(BER)

1. Introduction

Recently, a new universal radio interface, Bluetooth, has been developed enabling electronic devices to communicate wirelessly via short-range ad-hoc radio connections. The Bluetooth technology eliminates the need of wires, cables and the corresponding connectors between cordless or mobile phones, head-sets, personal digital assistants (PDAs), computers, notebooks, printers, projectors, etc. Bluetooth provides wireless interconnections among the electronic devices and peripherals used by individual. This network concept is called as personal area network, PAN. To provide global availability, the 2.4GHz industrial scientific and medical (ISM) unlicensed band is commonly used for low cost radios. An unrestricted access to the ISM spectrum exposes Bluetooth devices to a high level of interference[1-4].

Bluetooth devices undergo interference problems that can be classified into two categories. The first category is the inference caused by non Bluetooth devices. New proposed solutions for wireless PANs [5]and HomeRF[6] operate in the 2.4 GHz band while IEEE 802.11[7] and HIPERLAN Type I[8] operate in this band for wireless LAN. The microwave ovens are also users of the band at 2.45GHz. The second category is the interference caused by other Bluetooth connections. It is called mutual interference. The Bluetooth networks adopt ad-hoc topology called by piconet and scatternet. This topology allows that many Bluetooth devices can coexist within close proximity. It is likely to have several persons in proximity, each having an open Bluetooth connection between a mobile phone and a headset or a mobile computer as shown in Figure 1.

Mutual interference involving Bluetooth technology has been addressed by several research groups[9-11]. In [9], only packet error rate(PER) was considered with a hit probability and co-channel carrier-to-interference ratio, $(C/I)_{CO}$. The hit probability means the probability that two or more Bluetooth connections use the same frequency band. It was assumed that the transmitted and received power of all Bluetooth connections were equal and all Bluetooth connections were synchronized. That is unrealistic. In [10], the PER of asynchronous case was drawn. But there was no consideration about the signal power and $(C/I)_{CO}$. In [11], the PER is analyzed by empirical tests. To obtain the packet error probability, it adopts a outage probability, probability that the desired signal-to-interference (SIR) ratio is smaller than the desired SIR threshold, γ_{th}. In [9],[10], when a frame is hit by another frame that uses the same frequency, both frames are considered as corrupted. But if there are much differences between their signal powers, one frame may survive. In [11], if the SIR is smaller than γ_{th}, the packet is assumed to be corrupted. However, the packet error may not occur even in the outage probability case.

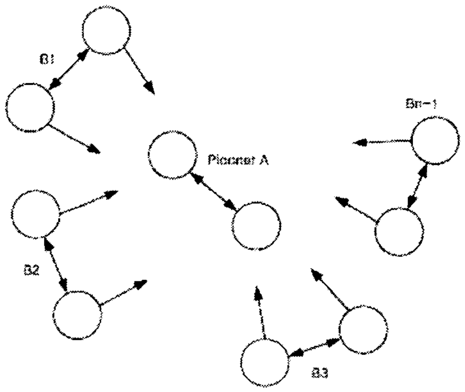


Figure 1. Interference Model between Independent Piconets

In this paper, the packet error probability (PEP) performance of Bluetooth networks under the mutual interference is analyzed and simulated. Not only the hit probability but also the SIR effect are considered. The PEP is extracted from the bit error rate (BER) and packet length.

This paper is organized as follows. In Section 2, the analysis of the packet error probability is analyzed considering. In Section 3, comparisons between analytic and simulation results are shown. Finally, this paper is concluded in Section 4.

2.Bit Error Rate Analysis between Independent Bluetooth piconets

2.1 Mutual Interference and Packet Error

It is assumed that two co-located piconets that are sufficiently close from one another such that a co-channel interference between two or more packets will affect each other. Because of the strong adjacent channel rejection requirement required by the standard, adjacent channel interference is not considered. The traffic in each piconet consume all the time slot, in other words, there are no empty time slots. The packet is assumed to be DH1 packet which occupies 1 time slot. A Bluetooth radio communication aims indoor environment, only distance dependent attenuation, also called path loss, is considered:

$$L_p(d) = \begin{cases} 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) & , d \le d_0 \\ 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + 10n\log_{10}\frac{d}{d_0} & , d > d_0 \end{cases}$$

where d and d_0 mean the distance and line of sight (LOS) respectively. Assume that the bit error rate can be described as a simple parameterized function of the instantaneous SNR ϒ as

$$P_s(\gamma, a, b) = ae^{-b\gamma} \qquad (1)$$

with a>0, b>0, ϒ=E_S/N_O (without interference) and E_S, N_O being the energy per received bit and the single sided thermal noise spectral density respectively. Assuming that errors due to AWGN are independent, the instantaneous block error probability (P_{BL}) , i.e., the probability to have at least an error in a block of symbols becomes

$$P_{BL}(\gamma, N, a, b) = 1 - (1 - P_S(\gamma, a, b))^N \qquad (2)$$

The above equations can be applied to the case that there are no interfering signals. Considering the interference signal, the signal-to-interference-plus-noise ratio (SINR) is used. The ϒ is replaced by γ_I:

$$\gamma_I = \frac{S}{\sum_j I^j + N} \qquad (3)$$

where S is the desired signal power,and I^j is the interference power due to the j th interfering piconet. Since the thermal noise is negligible, the SINR is considered to be the same with SIR.

To cope with erroneous wireless property, the Bluetooth adopts 1/3 forward error correction (FEC) in the accesscode and header of the packet. The 1/3 FEC can correct one bit error of the consecutive three bits. Hence, the block error probability for the FEC block is

$$P_{BL^{FEC}}(\gamma, N, a, b) = 1 - \left[\sum_{x=0}^{1}\binom{3}{x} P_S{}^x (1 - P_S)^{3-x}\right]^{N/3} \qquad (4)$$

,where P_S is P_S(ϒ,N,a,b). For simplicity, the FEC for the access code is assumed to be identical to the header.

2.2 Mutual Interference from a single Piconet

At first, two co-located piconets may be overlapped like Figure 2. Former research groups have assumed that just overlap of bits will destroy all. Under the assumption, The packet in Figure 2 will be corrupted if interfering piconet chooses the frequency that reference piconet uses. However, if signal power of the interfering piconet is relatively smaller than that of the reference piconet, the packet of interest may not be corrupted.

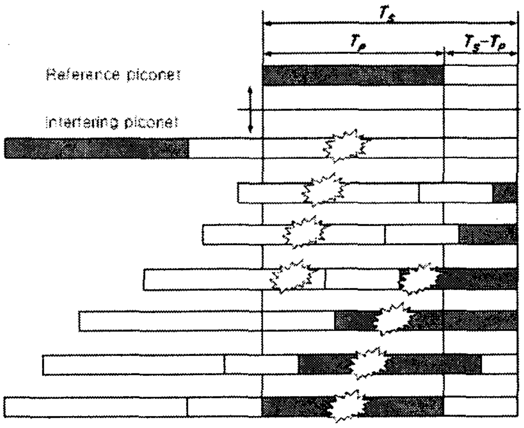


Figure 2. Expositiontointeference

Let the reference piconet and the interfering piconet denote piconet A and piconet B. Let T_S, T_P, and T_H denote the slot time, the packet length and the access- code plus the header length, respectively. The packet of interest in piconet A can be divided into two portions : non-interfered and interfered portion. The bit error rate (BER) of two portions are different because SNR or SIR are different. Therefore, packet error is drawn from the bit error rate. Depending on the time offset, one or two slots from the piconet B can interfere with the packet of interest in piconet A. Let the timing offset between two piconet denote x like Figure 3.

Over all possible offsets of the interfering piconet, there are single threatening, that means one packet can interfere the packet of interest, and double threatening with two packets. These threatens can be categorized into four cases like Table 1.

Here, bold font means that the threatening portion

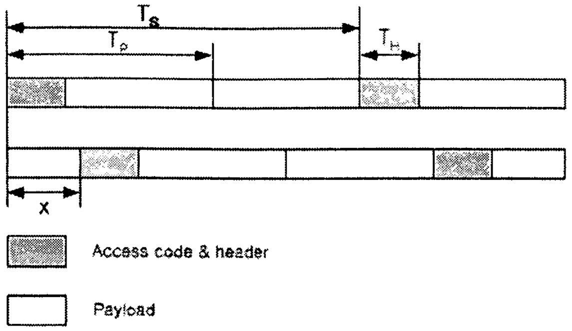


Figure 3. Relative Timing between two Piconets

Table 1: Bluetooth Interfering Cases

Case	Interfering Length	Timing Difference x
1	$T_P - x$	$0 \le x \le T_S - T_P$
2	$T_P + x - T_S$ & $T_P - x$	$T_S - T_P < x \le T_P$
3	$T_P + x - T_S$	$T_P < x \le T_S + T_H - T_P$
4	$T_P + x - T_S - T_H$ & T_H	$T_S + T_H - T_P < x \le T_S$

is FEC coded. Since, the timing difference is meaningful within slot time, T_S, the distribution of x is assumed to be uniform on [0,T_S], i.e., Pr{x=a}=1/T_S where a[0,T_S]. Bluetooth adopts frequency hopping spread spectrum with 79 frequencies, the probability of frequency collision is p_c=1/79.

Once the parameter a, b are determined, they are constants. Hence, $P_{BL}(\Upsilon,N,a,b)$ can be thought as function of ϒ and N, i.e., $P_{BL}(\Upsilon,N)$. Using above notations, the packet error probability of case 1, $P_{e,1}$, can be shown as:

$$P_{e,1} = p_C P_{BL}(\gamma_I, T_P - x) \cdot P_{BL}(\gamma, x) + (1 - p_C) P_{BL}(\gamma, T_P) \tag{5}$$

where the first term is the interfering case with the product of interfering and non-interfering part with frequency collision probability, p_c, and the second term means non-interfering case with $(1-p_c)$.

$$\begin{aligned} P_{e,2} = {} & P_{BL}(\gamma, T_S - T_P) \cdot \\ & \{p_C P_{BL}(\gamma_I, T_P - x) + (1 - p_C) P_{BL}(\gamma, T_P - x)\} \cdot \\ & \{p_C P_{BL^{FEC}}(\gamma_I, T_P + x - T_S) + \\ & (1 - p_C) P_{BL,FEC}(\gamma, T_P + x - T_S)\} \end{aligned} \tag{6}$$

In the case 2, the packet is divided into three as shown in Equation (6), where the first term is the non-interfering region and the second term is interfering region in the payload and the third one is interfering region in the access-code and header.

$$\begin{aligned} P_{e,3} = {} & P_{BL}(\gamma, T_S - x) \cdot \{p_C P_{BL^{FEC}}(\gamma_I, T_P + x - T_S) + \\ & (1 - p_C) P_{BL^{FEC}}(\gamma, T_P + x - T_S)\} \end{aligned} \tag{7}$$

where the first term is non-interfering portion and the second term is interfering portion in the access-code and header.

$$\begin{aligned} P_{e,4} = {} & P_{BL}(\gamma, T_S + T_H - x) \cdot \\ & \{p_C P_{BL}(\gamma_I, T_P + x - T_S - T_H) + \\ & (1 - p_C) P_{BL}(\gamma, T_P + x - T_S - T_H)\} \cdot \\ & \{p_C P_{BL^{FEC}}(\gamma_I, T_H) + (1 - p_C) P_{BL,FEC}(\gamma, T_H)\} \end{aligned} \tag{8}$$

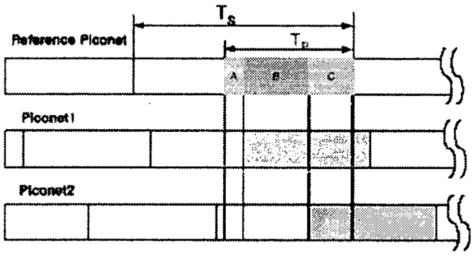
where the first term is non-interfering portion and the second and third term is interfering region in the payload and the access code and header, respectively.

From above equations and uniform distribution of timing offset, x, the average packet error probability can be expressed as

$$\begin{aligned} P_e = {} & \frac{1}{T_S} \int_0^{T_S - T_P} P_{e,1}(x)\,dx + \frac{1}{T_S} \int_{T_S - T_P}^{T_P} P_{e,2}(x)\,dx \\ & + \frac{1}{T_S} \int_{T_P}^{T_S + T_H - T_P} P_{e,3}(x)\,dx + \frac{1}{T_S} \int_{T_S + T_H - T_P}^{T_S} P_{e,4}(x)\,dx \end{aligned} \tag{9}$$

2.3 Mutual Interference from Multiple Bluetooth Piconets

In this section, the analytical model derived is extended to provide to multiple interfering cases. For simplicity, the distances between piconets are fixed to 10 m and that of the master and the slave is 1 m. Since there are more interferer in the operation range of the reference piconet, the signal-to-interference ratio (SIR) will be lowered than that of the one interferer. Also, the bit error rate (BER) will be larger than that of single interferer case because the BER is function of SIR. However, to get the closed form of the PER under multiple interferer is too complex. So, in this clause, one scenario of multiple piconets are given and both numerical and simulation results are given. Figure 4 shows the coexistence scenario of 3 piconets.



The packet of the reference piconet can be interfered by both Piconet1 and Piconet2. The interfering scenario can be classified into 3 cases according to the frequencies which the three piconets use.

- Case1: all three piconets uses the same frequency with probability p_c^2.
- Case2: only one of interferer piconet uses the same frequency with the reference piconet with $p_c(1-p_c)$.
- Case3: none of the piconets use the same frequency with $(1-p_c)$^2.

Let T_A,T_B, and T_C denote the duration of A,B, and C, respectively with 1 us resolution. Also p_A, p_B and p_C are the error probability in the A,B, and C of the packet. Then, the packet error probability is shown like following the product of where

$$p_{e,3piconets} = 1 - (1 - p_A)\cdot(1 - p_B)\cdot(1 - p_C) \quad (10)$$

$$\begin{aligned} p_A &= 1 - (1 - b_0)^{T_A} \\ p_B &= p_e \cdot \left\{1 - (1 - b_1)^{T_B}\right\} + (1 - p_e)\cdot\left\{1 - (1 - b_0)^{T_B}\right\} \\ p_C &= \sum_{k=0}^{2} \binom{2}{k} p_e^k (1 - p_e)^{2-k} \left\{1 - (1 - b_k)^{T_C}\right\} \end{aligned} \quad (11)$$

where bk represents the bit error rate under k interferer and the FEC is ignored. However, Equation (10) is not the closed form because the T_A, T_B, and T_C are not random variable here. In this way, the other multiple cases can be considered.

3. Comparision

The constants of BER, a and b, are drawn from the modulation curve of Gaussian freqency shift keying (GFSK) by the estimation theory. For simulation, Suitetooth of OPNET 9.1A is used. All nodes in each piconet are assumed to be in the heavy traffic situation, that means they always have packets to send. The DH1 packets are used for the data transmission.

3.1 Comparisons for Mutual Interference from single Piconet

The mutual interference model with single interfering piconet can be shown in Figure 5.

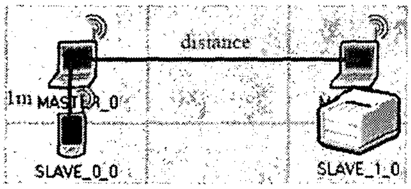


Figure 5. Single Interference Simulation Model in OPNET

Figure 6. shows the relationships among the SIR, BER and the distance between desired piconet and interfering piconet. The SIR is calculated using the indoor propagation model, and the BER is obtained from the modulation curve.

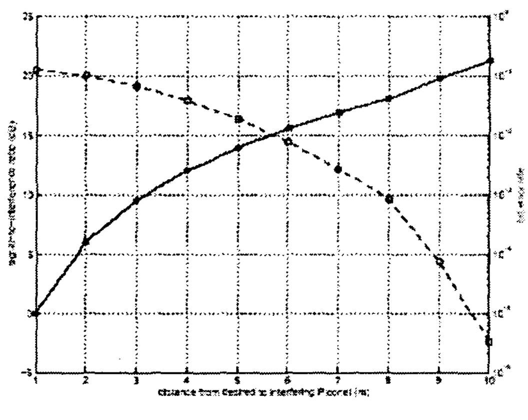


Figure 6. Numerical Relations among Distance, BER, SIR

The transmission range of the Bluetooth transceiver is known to be up to 10 m. Therefore, when using the same frequency and 0 timing offset, the desired packet always experiences the interference. However, as we can see in Figure 7, the packet can be exchanged to some extent without corruption. So, as we said, packets couldn't be assumed corrupted when just overlapped. The PEP of the numerical result is larger than that of the simulation because the numerical result doesn't consider the error correction capability of the access-code. And, there is also some estimation error.

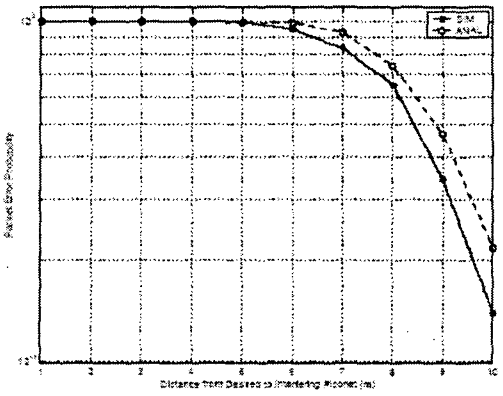


Figure 7. Comparison between Numerical and Simulation Results

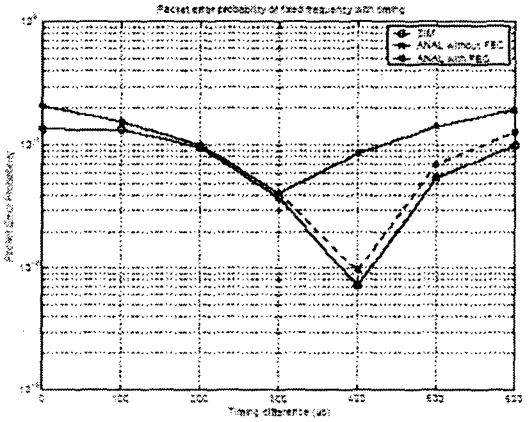


Figure 8. PEP vs timing with single interfering piconet under fixed frequency

Figure 8 shows the PEP with different timing offset when there is a single interfering piconet apart from 10m. The frequencies used in both piconets are the same in this case. By giving different timing offset, the overlap region of packets between reference piconet and interfering piconet varies. As you can see the figure, the analytic result is in accordance with the simulation result. The analytic results without the FEC are plotted also in Figure 8. Figure 9 is similar to Figure 8 except the frequency hopping. So, the PEP scaled down with p_c.

3.2 Comparisons for Mutual Interference from multiple Piconets

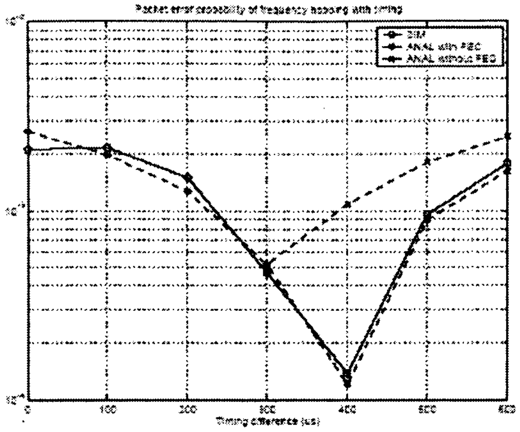


Figure 9. PEP vs timing with single interfering piconet under frequency hopping

The simulation model for multiple mutual interference is shown in Figure . For simplicity, the distances between piconets are fixed to 10m and that of the master and the slave is 1m.

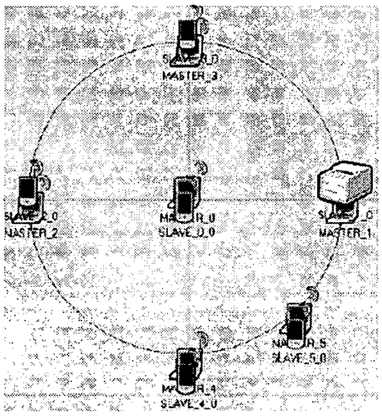


Figure 10. Mutual Interference Simulation Model with multiple Piconets

Figure 11 shows the PEP with multiple interferers, using the same frequencies, and without timing offset. Intuitively, the PEP increases as the number of the interferes increases.

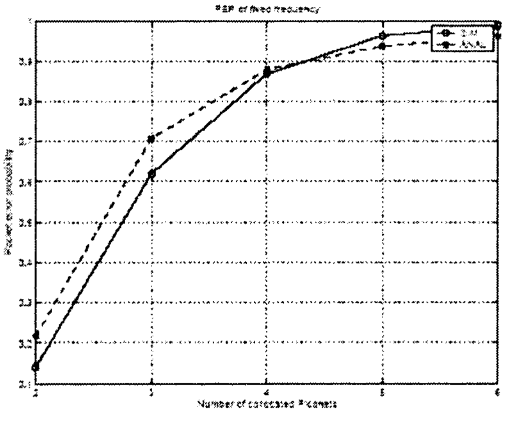


Figure 11. PEP vs multiple piconets under fixed frequency without timing offset

Figure 12 shows the PEP with multiple interferers, using the frequency hops, and without timing offsets. Intuitively, the PEP increases as the number of the interferes increases but it is reduced by the scale of the collision probability, p_c. As shown in the previous figures, there are some differences between the analytic and the simulation results that are made by the estimation error and the error recovery by the access code.

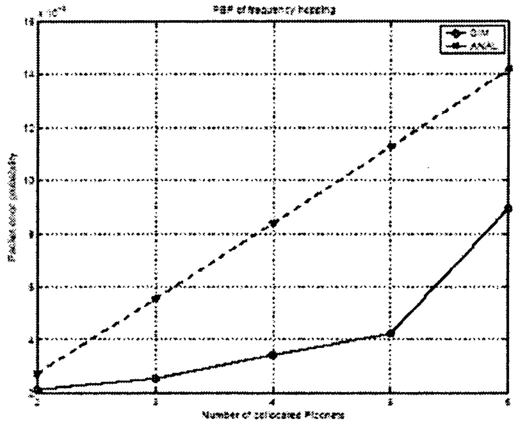


Figure 12. PEP vs multiple piconets under frequency hopping without timing offset

The PEP results with multiple interferes and with timing offsets are expressed as following tables. Table 2 shows the PEP using the same frequency and Table 3 shows the PEP with frequency hopping, respectively.

Table 2: PEP vs multiple piconets under fixed frequency with timing offset

# of collocated piconets	Analysis	Simulation
2	0.16329	0.13449
3	0.37744	0.41687
4	0.66273	0.71577
5	0.72107	0.8615
6	0.66822	0.65605

Table 3: PEP vs multiple piconets under frequency hopping with timing offset

# of collocated piconets	Analysis	Simulation
2	0.0020669	0.0020924
3	0.0012605	0.00075442
4	0.0053207	0.0036846
5	0.0060732	0.0037679
6	0.0015912	0.0015255

4. Conclusion

In this paper, the packet error probability (PEP) under the mutual interference is analyzed under additive Gaussian white noise (AWGN). The PEP is obtained using the BER (bit error rate) and the BER is function of signal-to-interference ratio (SIR). The BER is expressed as the exponential closed form by the estimation theory. The forward error correction (FEC) is taken into consideration calculating the PEP. By simulation, the analysis is validated.

This paper is motivated by the idea that if there are much differences between the desired signal power and the interfering signal power packet may survive unlike the former studies assumed that even single bit overlap cause the packet corruption. In addition, to obtain the PEP, the BER under interference is used. Therefore, the FEC effect can be considered. Therefore, the result of this paper is more realistic and can suggest coexistence criteria of Bluetooth piconets and scatternets.

[Reference]

[1] SIG Bluetooth, Specification of the Bluetooth system V1.1," 2001.
[2] J. Haartsen, Bluetooth-the unicersal radio interface for ad hoc, wireless connectivity, Ericsson Review, vol. 1, pp. 110{117, 1998.
[3] J. Haartsen, The Bluetooth Radio Systems, IEEE Personal Communications, vol. 1, pp. 28-36, 2000.
[4] J. Haartsen, Bluetooth-a new radio interface providing ubiquitous connectivity, IEEE Vehicle Technology Conference, vol. 1, pp. 107-111, 2000.
[5] Web document, IEEE 802.15 WPAN Wokr Group, http://www.ieee802.org/15/, 2002.
[6] HomeRF, Technical summary of the SWAP specification, 1999.
[7] IEEE Std.802-11, IEEE Standard for Wireless LAN Medium Access COntrol(MAC) and Physical Layer(PHY) specification, 1997.
[8] ETSI, High Performance Radio Local Area Network (HIPERLAN) Type 1 Functional specification, 1998.
[9] E.F.Meihofer S.Souissi, Performance evaluation of a Bluetooth network in the presence of adjacent and co-channel interference," IEEE Emerging Technologies Symposium: Broadband, Wireless Internet Access, p. 6, 2000.
[10] A.El-Hoiydi, Interference between Bluetooth networks-upper bound on the packet error rate, IEEE Communications Letters, vol. 5, pp. 245-247, 2001.
[11] I. Howitt, Mutual Interference between Independent Bluetooth Piconets, IEEE Transactions on Vehicular Technology, vol. 52, pp. 708 -718, 2003.