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Towards Performance Enhancement of Short Range Wireless Communications in Reliability- and Delay-Critical Applications

Yang Liu and Ye Liu
Department of Computer Science, University of Vaasa
PL 700, 65101 Vaasa, Finland
Email: yang.liu@uwasa.fi

1. Introduction

More and more applications demand highly reliable and low latency short range wireless communications nowadays, one extreme example of which is the wireless communication used in RoboCup Small Size League (SSL) robots (Liu et al, 2007). RoboCup is the world's top level international robotics competition held every year, and SSL is for a team of multiple fast-moving robots under a dynamic environment to autonomously play soccer game against another team. Due to the highly dynamic nature of the competition, the requirements and constraints for the wireless communication are extremely tight. The challenge is that wireless communication is involved in the control loop and therefore the reliability and propagation delay are vital factors which directly affect the team performance. Beside, various interferences with known and unknown frequency / transmission power usually present at the competition site, which is hazardous environment to achieve reliable and low latency performance for wireless communication. This study investigates the performance strengths and weaknesses of various short range wireless communications e.g. RadioMetrix, IEEE 802.11a/b, IEEE 802.15.4, DECT, Linx, etc, which are commonly used nowadays in different RoboCup SSL wireless communication implementations. Unfortunately most of these commercial solutions are not able to provide satisfactory performance to such kind of reliability- and delay-critical applications especially under interferences. In the case study, a typical commercial short range wireless communication module which has weak immunity to interference has been tested and its performance has been evaluated with test bed. An adaptive error correction and frequency hopping scheme (Liu, 2008) has been proposed to improve its immunity to interference and therefore enhance the wireless communication performance for reliability and delay-critical applications. Such scheme can be easily adopted to similar applications using short range wireless communications.

2. Communication System Design and Testing

2.1 Choosing wireless technologies

Many different wireless technologies have been considered for use in the robots. The main ones are: RadioMetrix 433 MHz and 869 MHz RF, IEEE 802.11a/b, IEEE 802.15.4, DECT, Linx, etc. While making decision which technology to choose, we also need to keep in mind about RoboCup's rules and regulations and also compliance with regulations of the country hosting the competition. Before the competition all teams should notify the local organizing committee of the wireless communication technology, power and frequency. To avoid direct interference, each team should be able to select between at least two carrier frequency bands before the match.

After experienced unsatisfied performance from the RF modules, the prospective choices are from IEEE 802.11a/b, IEEE 802.15.4, DECT and Linx. Among these wireless technologies, IEEE 802.11a/b is based on CSMA/CA and therefore considered not to be optimum solution for real-time applications. According to Tse et al (2005), the performance of IEEE 802.15.4 drops significantly where there are many 802.11 terminals connected to access points, which is the case at the competition site, and therefore this is not considered as optimum solution either. Both DECT and Linx are designed to support voice transmission capability and optimized for real-time performance, so the communication system for the new generation robot design will use these two and choose the one which will perform better during the competition, according to the opponent team's radio to be used.

2.2 Designing the test bed

The purpose of this testing is to observe and study wireless communication performance of Linx modules such as round trip delay, bit error, packet error, RSSI (Received Signal Strength Indication), and how they are affected by interference. A test bed has been built to carry out the tests and collect data to a PC. Both wireless transmitter and receiver modules are connected to an ARM7 microcontroller UART port. The packets which have been transmitted over wireless link are compared by ARM7 with the packages that have been received. The testing data are sent to PC for further processing. The timer feature is used to record the transmission time per each byte, and the result are also read by the microprocessor and sent to PC. Linx HP3 RF modules also provide a RSSI function which is connected to ADC so that a digital RSSI value can be read to indicate each byte's signal strength. The test bed simulates a full-duplex wireless transmission. Linx transmitter A will send data through channel A to Linx receiver B. Transmitter B will send what receiver B received through channel B to receiver A. In such way, we could measure the time delay for the round trip, RSSI for both channel A and B, error rate of the data, etc.

Much attention has been put to design PCB carefully following the standard industrial practices and choosing high quality components.

For testing purposes a test bed has been designed and implemented which will be able to work with both DECT and Linx modules. Here we present briefly some board design issues with some theoretical background when needed. The testing board is made of two parts: the mother board and the daughter board for LCD display and buttons, which will be mounted on top of the mother board.

The board can support both serial communication (through its DB9 female connector) and Ethernet connection (using RJ-45 XPort jack). Serial connection is left for downwards compatibility with the old server. It's connected directly to DECT and Linx modules. In the near future only Ethernet interface will be used to communicate with the server, and therefore in the testing board we use two XPort devices. One is connected directly to communication modules. The other one is connected to microcontroller to be able to set and control communication parameters, like RSSI values and communication channel number for monitoring and data logging to be used for further analysis.

Linx HP3 Series transmitter and receiver are high-performance RF modules (Linx 2007a, Linx 2007b) commonly used in wireless data transfer and industrial automation. They use popular 902-928 MHz frequency band. On the PCB we have possibility for serial channel selection of 100 channels by using microcontroller's I/O ports. Anyway in case of problems with microcontroller's operation during the competition we have provided also parallel selection of 8 channels using octal rotary DIP switches. For digital data transmission, Linx uses FSK modulation to ensure reliable performance. Equation (1) shows the FSK modulation formula. In FSK the modulating signal shifts the output frequency between two discrete values so called mark and space frequencies:

$$s(t) = \begin{cases} A_c \cos(2\pi f_1 t), & m(nT_b) = 1 \\ A_c \cos(2\pi f_2 t), & m(nT_b) = -1 \end{cases} \tag{1}$$

Therefore comparing to On-Off Keying modulation, FSK has increased noise immunity and ability to capture in the presence of multiple signals which is really helpful especially in such crowded band. Using those SIP style Linx modules we don't need any additional RF components (except of the antenna of course). Receiver has an exceptional sensitivity of -100 dBm typical.

The critical requirement for both modules performance was big ground plane on lower layer of PCB. To minimize losses we had to stick to the rules of designing microstrip as shown in Figure 1, the trace running between module and antenna.

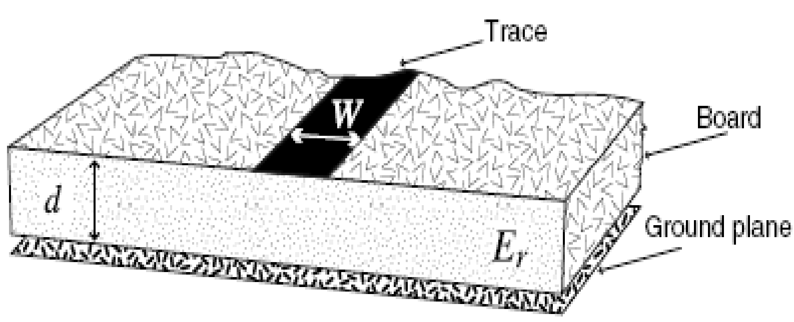

Fig. 1. Microstrip (Linx 2007b)

Microstrip design is based on Equation (2) and (3):

$$E_e = \frac{E_r + 1}{2} + \frac{E_r - 1}{2} \cdot \frac{1}{\sqrt{1 + 12d/W}} \tag{2}$$

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{E_e}} \cdot \ln(\dfrac{8d}{W} + \dfrac{W}{4d}) & \text{For } \dfrac{W}{d} \le 1 \\ \dfrac{120\pi}{\sqrt{E_e} \cdot (\dfrac{W}{d} + 1.393 + 0.667 \cdot \ln(\dfrac{W}{d} + 1.444))} & \text{For } \dfrac{W}{d} \ge 1 \end{cases} \tag{3}$$

E_r =Dielectric constant of PCB material

Another important thing is antenna's length. We have decided to use whip style antenna. Its optimal length can be calculated using Equation (4):

$$L = \frac{234}{f_{MHz}} \tag{4}$$

L is length in feet of quarter-wave length and f_{MHz} is the operating frequency in MHz.

Therefore in our case we will need two 8 cm long whip style antennas. The antennas are located as far as possible from each other and in the same line facing to the field with playing robots.

2.3 EMC and wireless performance testing

We have measured the testing board for radiated E-field emissions using European Union standard EN 55022 in EMC laboratory. This test measures unintentional E-field emissions from product in normal operating mode. Linx modules including a transmitter and a receiver have been tested. Simple application written in C and running on ATMega8535L microcontroller displays on LCD screen actual RSSI values. The board is connected with laptop computer outside EMC room with cross-over CAT5e cable. Client-server application written in Java constantly sends a packet which is passed to Linx transmitter and waits for response from the receiver, to check if the received value is correct. At the end of the measurement there is a table showing in percentage how many errors occurred at which particular frequencies.

The channel is set to 69. For these settings transmitter frequency should be 919.87 MHz. In EMC laboratory, jamming signals are feed at fine steps from 915 to 925 MHz. We were observing error rate occurring for different frequencies and in the same time we were recording Received Signal Strength Indicator (RSSI) value. The results from the measurements are shown in Table 1 and plotted in Figure 2.

F [MHz]	Errors [%]	RSSI
915	0.00	140
916	0.05	142
917	0.17	139
918	0.69	135
919	96.71	120
920	0.56	125
921	0.14	130
922	0.00	135
923	0.13	129
924	0.23	127
925	1.32	130

Table 1. Error rate and RSSI measurements

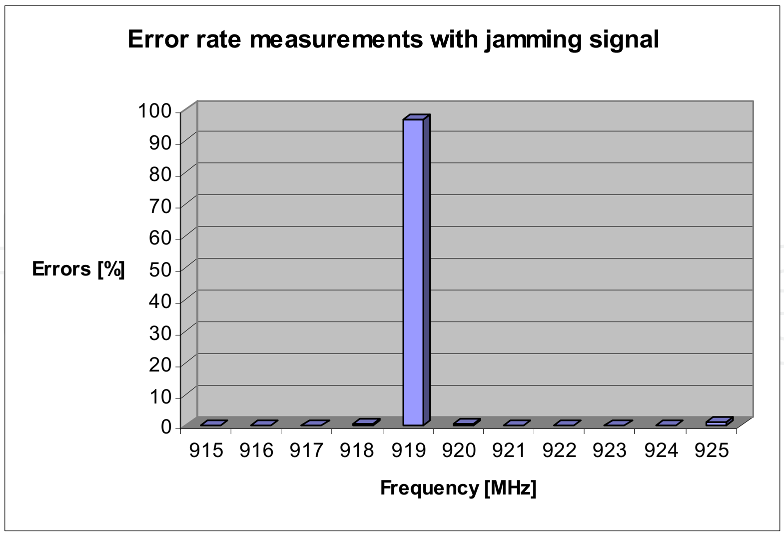

Fig. 2. Error rate measurements with jamming signal

As expected, most errors have occurred on transmitter frequency 919 MHz which is better visible in Figure 2 showing percentage of errors for given frequency. The value of RSSI was much lower around 919 and 920 MHz and it was varying rapidly around the values shown in Table 1, but the value has never gone below 120. The adjacent channels, although affected by the jamming frequencies too, have significantly lower error rates. This indicates that frequency hopping can be used as one very effective solution to improve the immunity to jamming signals.
Signal to Noise Ratio (SNR) variable in the formula below is defined as the signal to noise ratio. The probability of error can be calculated for a receiver system using non-coherent FSK modulation. The system is modelled with two matched filters which are centred at f1 and f2 with envelope detectors summed to a decision circuit. Equation (5) can be used to calculate the probability of error for non-coherent FSK modulation:

$$P_{\varepsilon} fsk_{SNR} = \frac{1}{2}\exp(-\frac{SNR}{4}) \quad (5)$$

Real-life performance of Linx wireless communication has been also intensively investigated in terms of round trip delay, bit error rate and packet error rate, etc, by interfering with simulated jamming signals, and results are shown in Figure 3.
The typical round trip time delay for Linx wireless transmission is around 209 μs to 809 μs after deducting the processing time. Under heavy interference (10 V/m) the most common bit error rate is 3 bits per byte. Hence, a 3-bit error correction scheme should be sufficient to significantly improve the reliability of wireless performance. Besides error correction, frequency hopping is also employed to resist interferences. The RSSI levels of all channels are scanned and a black list is generated so that all the bad channels are excluded from the random frequency hopping sequence to ensure the hopping channel quality, and therefore improve the communication performance even further.
Figure 4 shows a detailed snapshot of good quality channels. The sequences of the plot are RSSI, Delay, Bit Error Rate, and Packet Error Rates. The data cursor tells that while jam frequency are located among channel 40 to channel 48, the transmission give a better performance with strong RSSI, evenly distributed time delay, low bit error rate and low

packet loss rate. Among channel 53 to channel 74, the transmission gives an even better performance. It can be concluded that, if the transmission is allocated from 1 to 10 channels below or above the jamming frequency, the wireless performance is significantly better. This has proved again that frequency hopping scheme will be quite effective to improve the existing wireless transmission.

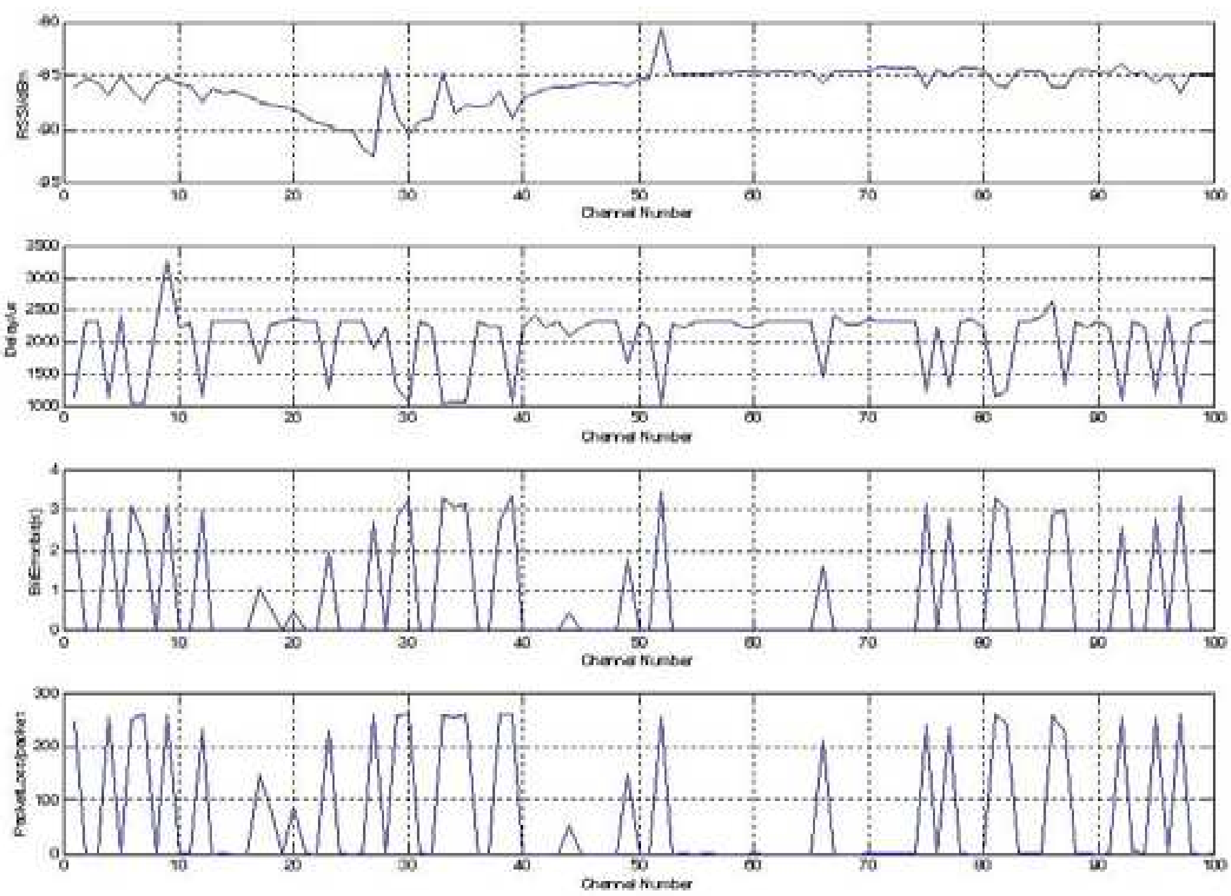

Fig. 3. Performance evaluation of RSSI, delay, bit error rate, packet loss rate

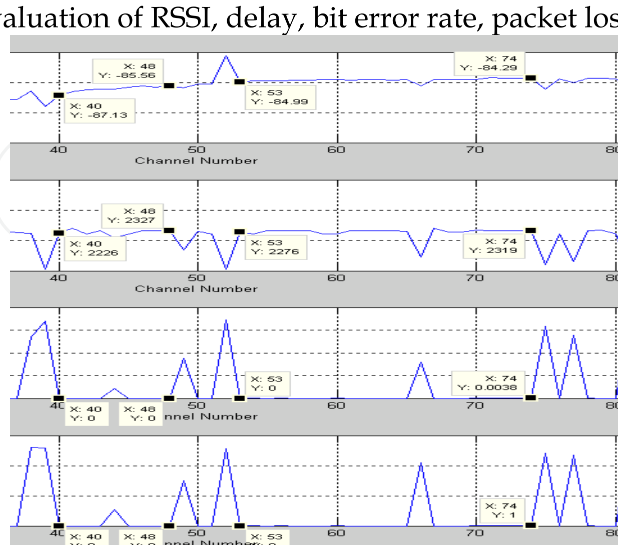

Fig. 4. Performance of RSSI, delay, bit error rate, packet loss rate in good quality channels

3. Analysis and Enhancement of Wireless Communication Performance

3.1 General analysis of improvements proposals

Reliable communication is critical for success in the competition. Most intelligence and all tactics are processed on the centralized server so if there is excessive data error or delay in the communication with the server, robots cannot achieve reliable real-time performance. In case of this application, propagation delay in the communication is much more critical than the throughput. Specific data transmission doesn't require high throughput but working with real-time systems means that information which will come to receiver too late is useless, and will result in foul or loosing a goal during competition.

During the tests it has been noticed that 96.71% of errors occur on the same frequency as the one set on Linx module. Any concurrent transmission on that frequency causes excessive errors and decreases reliability. In case of very small SNR the system doesn't work at all.

Because the described communication system has to work in very noisy environment we have to consider use of additional error detection and correction algorithms to improve communication's reliability. One of the improvements could be dynamic checking for channel with the highest SNR and choosing the best channel for communication purpose.

Other idea is to use two antennas inside the robots making use of antenna diversity, the fact that fading is space dependant and one of the antennas will receive stronger signal than the other. This is important especially that the robots move fast and can change position and orientation rapidly.

Because the data is sent to robots using broadcast, not point to point, so there are more than one channel which could be used. Therefore there is possibility to use frequency diversity, using two channels to communicate with robots (to broadcast the same data). The channel which is more probable to have correct data is the one with the highest SNR.

Finally, from the measurement results obtained from the test bed, it can be concluded that utilizing frequency hopping is probably the most effective solution to improve the wireless communication performance without changing much existing communication system structure.

3.2 Adaptive frequency hopping

An adaptive frequency hopping scheme with duplex link is proposed as an improvement solution. Frequency hopping is a powerful solution towards to interference and multi-path fading. As normal frequency hopping system, a hop-sequence generator has to be determined, so that the frequency hopping system will avoid the congested channel and transmit the data in clear channel. The hop-sequence generator is determined based on the link quality testing results as well as the analysis of wireless communication theory.

Frequency hopping is categorized into slow hopping and fast hopping. By slow hopping, more than one data symbol is transmitted in same channel. Fast hopping change frequency several times during one symbol (Rappaport, 2001). The pattern of channel usage is called the hopping sequence (Jochen, 2001). Explain the notion of hopping sequences in a more practical way is that how to determine the next channel to hop. There are two types of hopping sequence: random hopping sequences and the deterministic hopping sequences. In this study a hopping system with slow deterministic frequency hopping sequence is focused. Compare with other kinds of wireless communications, HF communication selectively fading because of the multi-path propagation and abundance interference from others.

Hence, a channel with sustaining stable signal-to-interference ratio, SIR is normally used for a narrowband communication, and new channel is used according to the same SIR criteria when the previous channel quality changes. Narrowband schemes will not work as expected when there is noise burst although it is very efficient while slowing changing interference and fading environment is engaged. For wideband communication, a random frequency hopping schemes together with forward error correction, FEC method, the short noise burst will not effect wideband transmission; it is protected from jamming transmission and has low probability of interception.
The improvement proposal is meant to combine the advantage in of both narrowband and wideband schemes. Additionally, from previews EMC test results in RSSI tells each channel's quality so that a "bad channel" list can be generated. Therefore, the improvement proposal is determined, using a wideband frequency hopping scheme that would avoid known interference: the "bad channels". This can be done by functionalized one of the duplex channel as the feedback channel. The feedback information contains the channel numbers which are in use. The selection of active channels is based from EMC RSSI testing results, the channel RSSI which is lower than -95 dBm is considered as "bad channel". This system is an adapted frequency hopping system which can utilize the existing hardware functionalities to achieve the optimized wireless performance.
For this duplex communication system, the selection of which frequencies to be used is based on the feedback from uplink. As motioned before, the downlink transmitter A transmit the data, at the receiver B side the RSSI value of downlink which in this case is equivalent as SIR, is measured. At the receiver side a link quality analysis scheme is implemented, once the SIR is below the criterion, for instance, -95 dBm, LQA will determine that the channel needs to be switched. After the performance of the hopping sequence generator, the new channel number is send to the transmitter over the uplink.
In this proposed system, the uplink can be immobile and used for only sending feedback to downlink. If the downlink sends a packet with chips with each chip contain one channel symbol, and the uplink will send chips as feedback. Since the uplink's feedback is not totally reliable, therefore assume that the transmission with one bit per chip in Equation (6):

$$C_f = N_a \log_2 N + C_{OH} + R_\tau \tag{6}$$

$$N = TotalAvialableChannels = 100$$
$$N_a = ActiveChannels$$
$$C_f = ChipsOnFeedback$$
$$C_{OH} = FeedbackOverhead$$
$$R = ChipRate$$
$$\tau = propogationTime + LOADelay$$

During the EMC test, an RSSI testing for each channel is also measured. This can indicate each channel's quality from SIR aspect. The test is done by setting the jamming frequency at channel 27 and let the transmission carry out from channel 1 to channel 100, and then the same procedure while jamming frequency is set at channel 75. The result is shown in Figure 5. The green curve in Figure 3 presents the RSSI curve based on 100 channels' transmission while jamming frequency is set at channel 75, and the red curve in Figure 3 presents the RSSI curve while jamming frequency is set at channel 27. From this data, a "bad channel" black list can be generated.

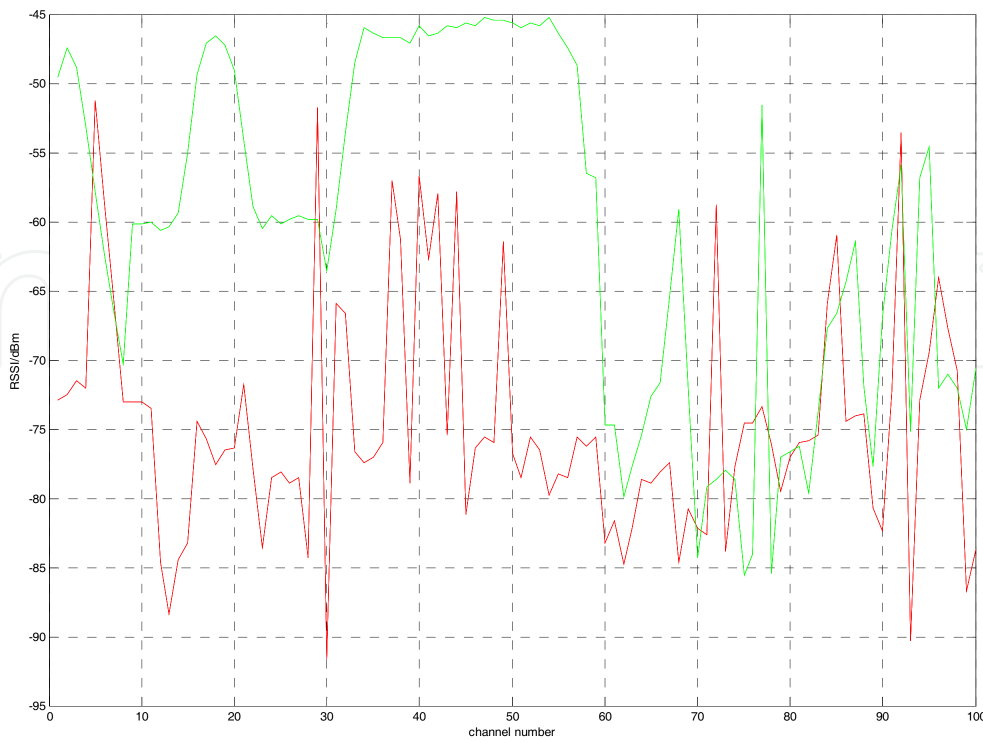

Fig. 5. Channel quality measurement: RSSI

3.3 Interference model and performance analysis

Interference always exists to any wireless system, in the improved system RSSI and the bit error rate is still important in aspect to determine whether if proposal is an improvement.
In this system, channel hops due to the SIR changes. Some of the channels are crowed while others are clear. Therefore, in the analyses, a simple two state channel model, "Gilbert-Elliot Model" (Gilbert, 1960 and Elliot, 1963) is used. "Gilbert-Elliot Model" is a two-state Markov chain (Wang et al, 1995) with states named "Good" and "Bad". According to this model, each of the channels may either be in a congested condition or clear. The classification is made due to received signal quality which means that except the interference, the two-state model also includes other transmission aspects, such as the signal strength. The bad state will be described as a channel (BSC) with a high bit error probability while the good state corresponds to a channel with a low bit error probability. Assume that all the transitions between the two states may be modelled by a Markov chain as shown in Figure 6.

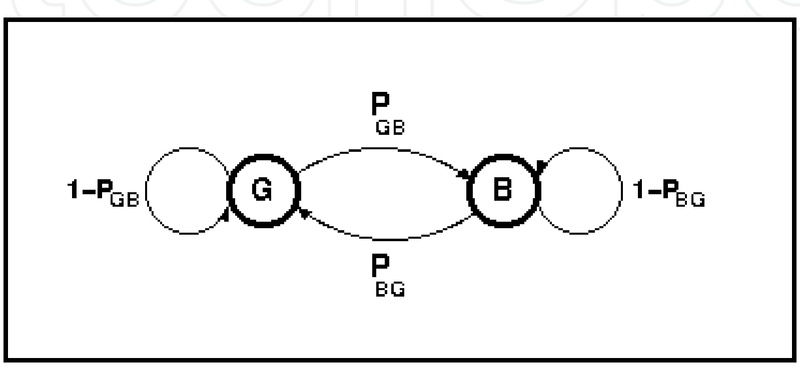

Fig. 6. A two-state Gilbert-Elliot model (Kanal et al, 1978)

The probability of leaving bad or good states will denote as n, m, and the occupancy of the frequency band by Q. Also assume that the average duration the transmission stay in the bad state is t (Andersson et al 1991 and Bröms 1991). As we know that the congestion of the channel is based on the SIR, the noise level and also the transmit power, higher the transmission power the lower the occupancy. According to Zander et al (1995) the probability of using a bad state channel is:

$$Q = P_B = \frac{n}{n+m}; \tag{7}$$

$$m = \frac{1}{t}; \tag{8}$$

$$n = \frac{1}{t} \cdot \frac{Q}{1-Q}; \tag{9}$$

Estimating the performance of the proposed system, the bit error probability is time-dependent, so assume that M channels being in a bad state at chip i, and the probability of error in chip i is P_i:

$$E\left[M_i \middle| M_0 = x\right] = x\left(1-(n+m)\right)^i + N_a \cdot n \frac{1-\left(1-(n+m)\right)^i}{n+m} \tag{10}$$

Assuming random hopping schemes select each of the active channels with equal probability, therefore:

$$P_{i(x)} = \frac{N_a - E\left[M_i \middle| M_0 = x\right]}{N_a} P_G + \frac{E\left[M_i \middle| M_0 = x\right]}{N_a} P_B \approx P_G + \frac{E\left[M_i \middle| M_0 = x\right]}{N_a} P_B \tag{11}$$

And assume that:

$$P_G << P_B; E\left[M_i \middle| M_0 = x\right] << N_a$$

Combining Equation (10) and (11) yields:

$$P_{i(x)} \approx P_G + \left(\frac{x}{N_a}\left(1-(m+n)\right)^i + n\frac{1-\left(1-(m+n)\right)^i}{m+n}\right) P_B$$

$$= P_G + P_B \frac{n}{n+m} - P_B\left(\frac{n}{n+m} - \frac{x}{N_a}\right)\left(1-(n+m)\right)^i$$

$$= P_G + P_B Q - P_B\left(Q - \frac{x}{N_a}\right)\left(1 - \frac{1}{(1-Q)t}\right)^i$$

Removing the condition x and can see that the probabilities of error in chip i:

$$P_i = P_G + P_B \cdot Q - P_B\left(Q - \frac{E[M_0]}{N_a}\right) \cdot \left(1 - \frac{1}{(1-Q)\cdot t}\right) \tag{12}$$

If i approximately is linear, than error probability would be:

$$P = \frac{1}{L} \cdot \sum_{i\_1}^{L} P_i \approx P_G + P_B \cdot \left[\frac{E[M_0]}{N_a} + \frac{L}{2}\left(n - \frac{E[M_0]\cdot(n+m)}{N_a}\right)\right] \tag{13}$$

Equation (13) is dependent on the value of M_0 and if assume that B is the number of bad channels in active channels, and L_f is the duration of the bad states may change, then:

$$E[M_0] = QN_a - \left(QN_a - E[B]\right) \cdot \left(1 - \frac{1}{(1-Q)\cdot t}\right)^{L_f} \approx QN_a - \left(QN_a - E[B]\right)\left(1 - \alpha L_f\right) \tag{14}$$

where:

$$\alpha = \frac{1}{(1-Q)\cdot t}$$

Because bad channels are binomially distributed so that:

$$E[B] = \sum_{i=0}^{N_a}(N_a - i)\binom{N}{i}(1-Q)^i \cdot Q^{N-i} \tag{15}$$

Imagine more complex case which there is a probability P_f that a feedback message may be lost and no changes will be made until the last packet is send. Therefore an extended feedback time is assumed as $L + 2L_f$, this gives:

$$\begin{aligned} E[M_0] &\approx 1 - P_f\left[QN_a - (QN_a - E[B])(1-\alpha L_f)\right] + P_f\left[QN_a - (QN_a - E[B])(1-\alpha(L+2L_f))\right] \\ &= QN_a - (QN_a - E[B]) \times \{1 - \alpha(L_f + P_f(L + L_f))\} \end{aligned} \tag{16}$$

From the equations above, the frequency hopping has been implemented and simulated with Matlab. Figure 7 shows the performance comparison with and without frequency hopping. With the proposed frequency hopping solution, the BER can be significantly reduced especially in bad channel conditions with low RSSI, compared to the performance without frequency hopping. This has proved the proposed system can well perform the transmission, and the best performance will be obtained if using fixed rate block codes with ideal interleaving and a soft decoder. Also the smaller the packet size gets, the lower the probability of error rate.

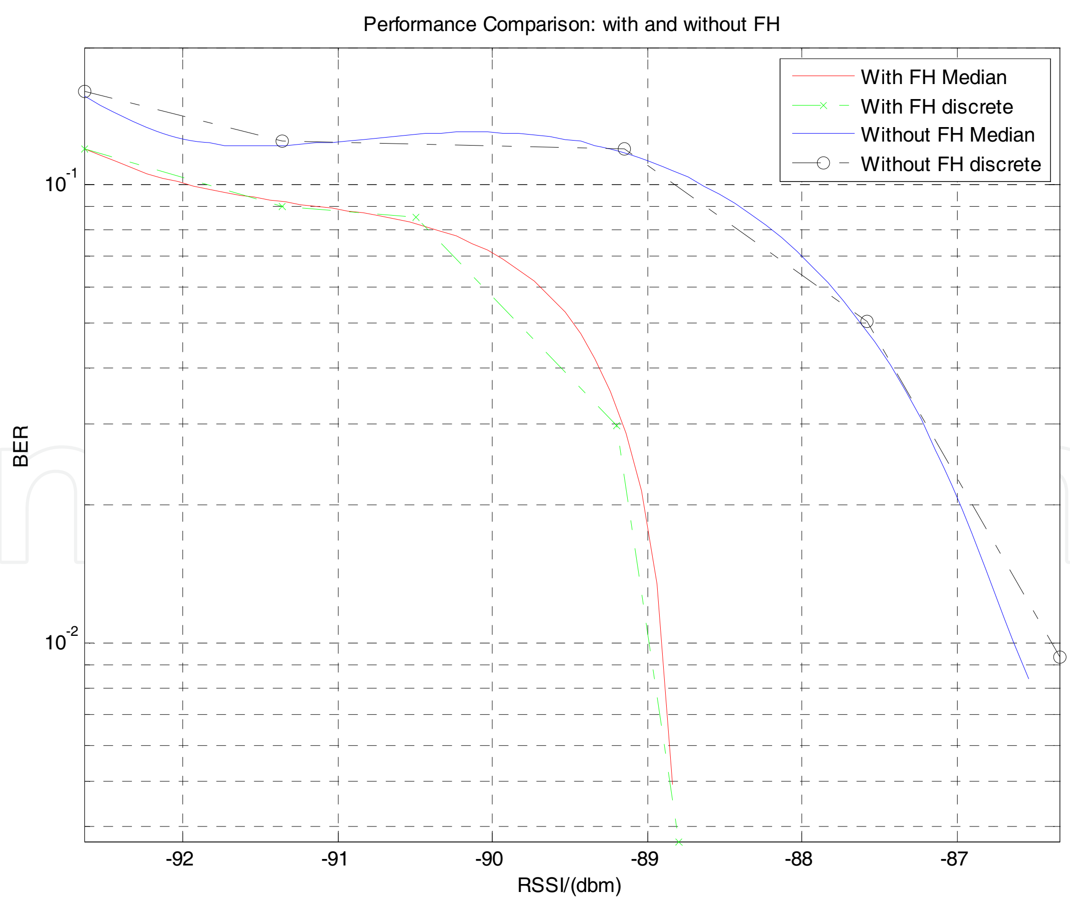

Fig. 7. Performance comparison: with and without frequency hopping

4. Conclusion

In this chapter, we have investigated different wireless technologies in order to optimize the wireless communication performance in application of RoboCup. Linx wireless communication technology is intensively tested using self developed test bed and EMC measurements, and its performance has been analyzed.

Reliable and low latency wireless communication ensures smooth and accurate control of fast dynamic process and is critical for success not only in RoboCup competition but also in many industrial automation applications where short range wireless communication technologies are used to replace existing cables. The prototype test bed with EMC measurements along with RoboCup application forms an ideal real world testing and analytical environment for various wireless communication technologies, to find out how different jamming signals affect their performances and therefore to make further improvements possible.

An adaptive frequency hopping scheme has been proposed to improve the immunity of interference of commercial short range wireless communication and therefore enhance the wireless communication performance. With the test bed to evaluate the wireless communication performance, the adaptive frequency hopping scheme can significantly reduce the bit error rate and packet loss rate. In future research, the proposed adaptive frequency hopping scheme will be adopted to other wireless links to be evaluated further.

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Mobile and Wireless Communications have been one of the major revolutions of the late twentieth century. We are witnessing a very fast growth in these technologies where mobile and wireless communications have become so ubiquitous in our society and indispensable for our daily lives. The relentless demand for higher data rates with better quality of services to comply with state-of-the art applications has revolutionized the wireless communication field and led to the emergence of new technologies such as Bluetooth, WiFi, Wimax, Ultra wideband, OFDMA. Moreover, the market tendency confirms that this revolution is not ready to stop in the foreseen future. Mobile and wireless communications applications cover diverse areas including entertainment, industrialist, biomedical, medicine, safety and security, and others, which definitely are improving our daily life. Wireless communication network is a multidisciplinary field addressing different aspects raging from theoretical analysis, system architecture design, and hardware and software implementations. While different new applications are requiring higher data rates and better quality of service and prolonging the mobile battery life, new development and advanced research studies and systems and circuits designs are necessary to keep pace with the market requirements. This book covers the most advanced research and development topics in mobile and wireless communication networks. It is divided into two parts with a total of thirty-four stand-alone chapters covering various areas of wireless communications of special topics including: physical layer and network layer, access methods and scheduling, techniques and technologies, antenna and amplifier design, integrated circuit design, applications and systems. These chapters present advanced novel and cutting-edge results and development related to wireless communication offering the readers the opportunity to enrich their knowledge in specific topics as well as to explore the whole field of rapidly emerging mobile and wireless networks. We hope that this book will be useful for students, researchers and practitioners in their research studies.

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Slavka Krautzeka 83/A
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Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821