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# Antenna Diversity Techniques for Bluetooth Communication

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**Abstract-** In order to cope with the environmental impacts on Bluetooth data transmission diversity techniques were examined. A Bluetooth antenna diversity demonstrator was developed. Extensive experimental investigations documenting the significant improvements of data communication employing diversity have been done. It was shown that the effects of multipath and fading can be combated to a large extent by antenna diversity. Thus, antenna diversity was found to be a powerful technique for improving the quality of Bluetooth links.

## 1. Introduction

Presently, Bluetooth is the fastest growing wireless communication technology. Operating in the 2.4 GHz ISM-band and based on a frequency hopping physical layer, it enables different types of portable devices to form short-range wireless ad-hoc networks. Mobile phones and PDA's as well as car equipment, refrigerators, even luggage have been published as Bluetooth carrying objects. Bluetooth will be an integral part of the convergence of the wireless and the internet world and will cover preferably, but not only, personal area networks (PAN). It will be the interface to the outer world, in particular to cellular networks and hot spots [1], [2], [3].

Industrial plants consist of many devices interconnected in different ways. Simple data collection units, more intelligent devices (sensors with built in intelligence, single loop controllers or programmable controllers) and supervisory systems. These devices are interconnected using many different communication protocols and media, which in some cases be replaced with Bluetooth wireless technology. Serial cable replacement, combination of Bluetooth and Internet technologies, industrial access points, wireless sensors

and actuators can be industrial uses of Bluetooth.

Bluetooth involves highly sophisticated methods for packaging, encryption and error correction of data and for radio resource sharing. But, still, Bluetooth transmits data via a radio channel. The application scenarios use their own radio channels due to the individual topology of the radio link.

To examine the performance of Bluetooth, simulations and numerous measurements have been done [4], [5]. Also, data rate measurements in different environments have been performed [6]. It was found that Bluetooth combines performance characteristics of narrow band transmission with the advantages of spread spectrum communication.

Data communication requires a reproducible Quality of Service (QoS), i.e. negotiated performance is to be granted during operation. Quality of service means a predefined and negotiated data rate, delay, and error rate. Since the error rate and the delay are strongly related to the data rate, we focus our present investigations on the data rate.

A signal passed over a wireless channel is affected by pathloss, narrow and wideband fading, and co-channel-interference [7], [8], [9]. The impulse response of the wireless channel is time variant and depends on the particular location. In general a deterministic approach is not feasible. Estimations can be made with statistical models [4], [5].

To cope with multipath fading and also with co-channel interference, BT applies FHSS (Frequency

Hopping Spread Spectrum). Single data packets are transmitted using one of 79 carrier frequencies with a spacing of 1 MHz. BT employs a pseudo random hopping sequence with 1600 hops/s, rather fast compared to other FHSS systems in the 2.4 GHz ISM band (802.11, homeRF, etc.). Although BT uses a 83.5 MHz wide frequency band to transmit raw data at a rate of 1 Mbit/s, it only occupies a bandwidth of about 1 MHz while transmitting. As modulation scheme BGFSK (Binary Gaussian Frequency Shift Keying) with a modulation index of 0.28-0.35 is used. The Gaussian pulse shaping reduces the covered bandwidth dramatically [10].

Most of the short range wireless communication technologies use the 2.45 GHz ISM band and therefore have to cope with interference. Furthermore, indoor communication is strongly affected by shadowing and reflections. This results in radio channels with only statistically predictable parameters variant in time and frequency. Narrow band systems perform only poor under such circumstances.

With Bluetooth, the packets transferred consecutive in time do not use the same frequency, thus avoiding the drawbacks of the narrowband transmission. As has been investigated in [4], [5], the link performance obeys the rules for narrow band systems and additionally depends on the fading of the individual channels occupied. Therefore all methods of improving the physical layer have to be frequency agile. As such an approach, we developed a Bluetooth antenna diversity demonstrator. In the following Section the demonstrator is described. Then in Section 3 the setup for our measurements is explained and in Section 4 the results of the experiments are discussed. A conclusion summarizes our work in Section 5.

## 2. Bluetooth Diversity Demonstrator

The medium access protocol for Bluetooth communication is a packet-based, Time Division Duplex (TDD) polling scheme. The transmission channel is divided into time slots, each 625µs in length. In the TDD scheme (Fig. 1), master and slave transmit alternatively. In Fig. 2 practical examples for the transmitted and the received signals are given.

Beam steering is the main principle of our Bluetooth diversity module. Diversity is controlled by sampling the received signal during the ‘Guard Time’ interval. This interval is used to get information about the incoming wave and to choose the optimum antenna configuration. When the receiving module takes over transmission, it uses the same antenna configuration. This procedure is repeated for each slot. Since the beam steering is done during the ‘Guard Time’, it does not reduce data rate.

A photo of the demonstrator is shown in Fig. 3 and

the basic hardware diagram sketched in Fig. 4. The demonstrator has a single base band unit, two radio units, one micro controller unit, an antenna matrix and two antenna connectors. The antenna connectors are separated by  $\lambda/2$ , providing a choice between integrated or external antennas. The demonstrator is physically separated into two PCB modules, the Bluetooth diversity module and the micro controller module.

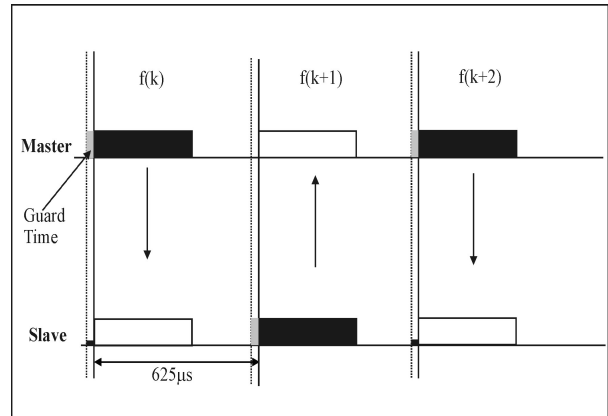
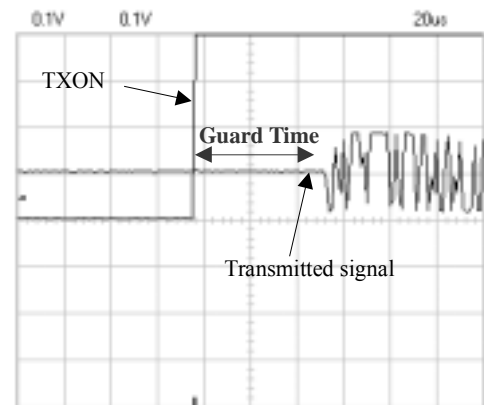
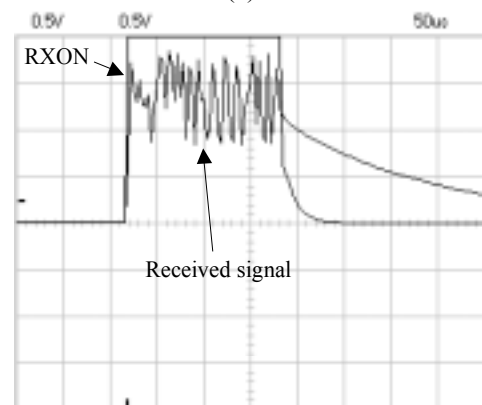


Figure 1: TDD and timing



(a)



(b)

Figure 2: Measured transmitted (a) and received (b) signals

The Bluetooth diversity module has two radio units, however, the base band unit receives its signal from only one of these. The micro controller decides between the radio units according to the Received Signal Strength

Indicator (RSSI) signals. Bluetooth baseband controller has an on-chip asynchronous serial interface UART (Universal Asynchronous Receiver and Transmitter) which allows the communication between the host (PC) and the Bluetooth baseband controller in full duplex mode. Baseband controller has an interface to the transceiver and they make a complete Bluetooth chipset solution.

The antenna matrix (Fig. 5) includes four switches. The signals from antenna 1 and 2 are combined according to the switch settings. Antenna matrix consists of two identical parts, each for every radio part. There are also four control signals SWITCH0/3. These are output signals from the micro controller who controls the microwave switches and determines their position in the specific moment (during receive and transmit period).

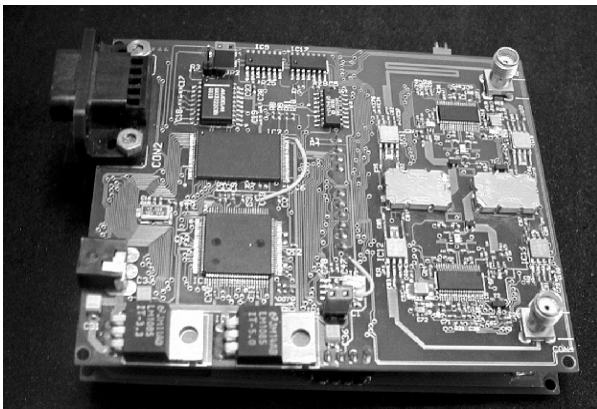


Figure 3: Bluetooth diversity module

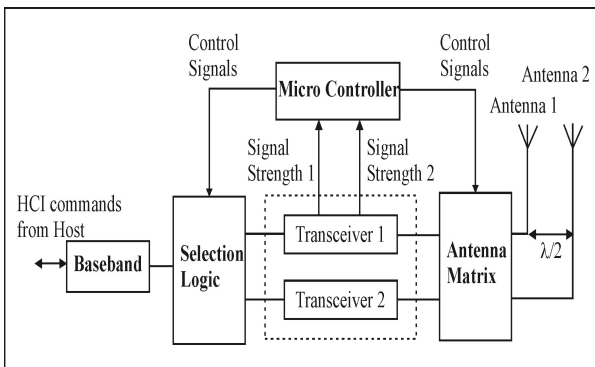


Figure 4: Basic block diagram of the diversity demonstrator

The module supports three operational modes: mode one is normal Bluetooth operation without diversity. The second mode enables space diversity (Fig. 6): the signals coming from the two antennas are compared in strength and the stronger one is chosen by the micro controller for further processing in the baseband. Angle (beam) diversity is the third mode (Fig. 6): the signals from the two antennas are combined in the antenna matrix to obtain two orthogonally directed antenna beams (Fig. 7). As in case of space diversity, the stronger beam signal is

processed in the baseband.

The micro controller board, determines the antenna diagram by controlling the position of the four antenna switches in the antenna matrix.

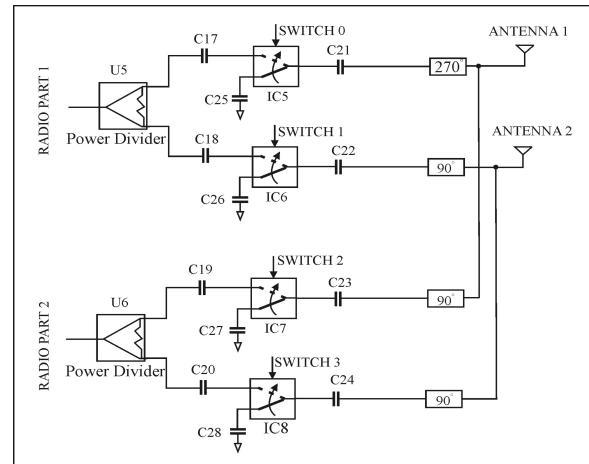
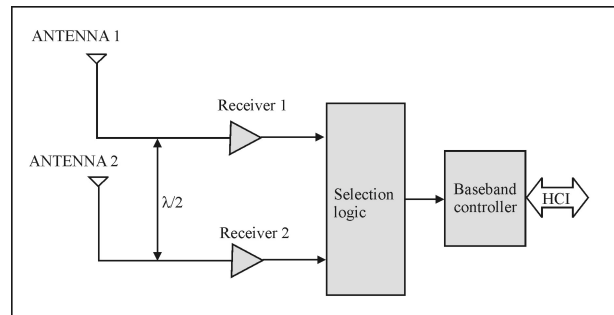
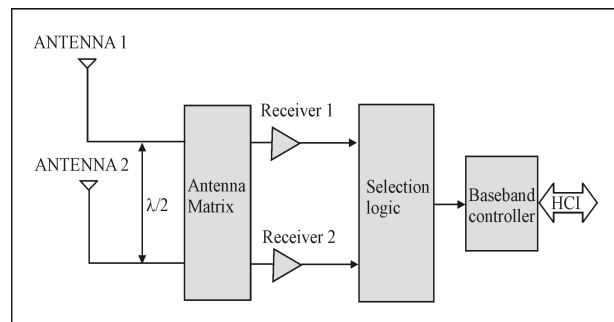


Figure 5: Basic block diagram of the antenna matrix

If the Switch0/3 is in the position that connects antenna terminal to ground, it is considered to be in OFF position, otherwise, the switch is in ON position. Switch in OFF position must not load antenna terminals; therefore, the 90 or  $\lambda/4$  transformers are introduced in the path between switch and corresponding antenna terminal.



(a)



(b)

Figure 6: Basic block diagram of space diversity (a) and angle diversity (b)

Furthermore, production of two orthogonal antenna beams requires in-phase (or 0 phase difference) and out-phase (or 180 phase difference) antenna feed. Due

to this, a  $270^\circ$  ( $90^\circ + 180^\circ$ ) line is introduced in the path between Antenna1 terminal and Switch 0, both to serve as  $\lambda/4$  transformer and  $180^\circ$  phase shifter. In practice, transformer line length is shorter than  $\lambda/4$  wavelength, as switches in OFF position are inductive in nature.

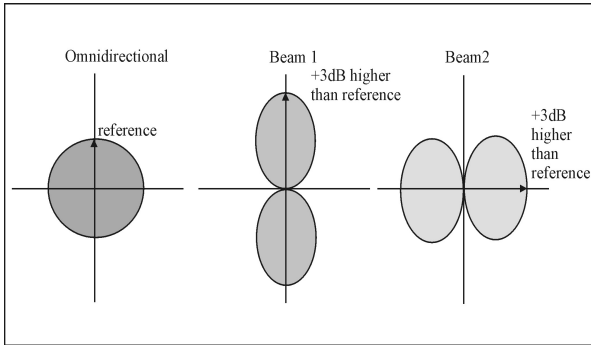


Figure 7: The beams used in the angle (beam) switching mode of operation

### 3. Measurements

The Bluetooth link was established using two notebook computers (hosts) connected to Bluetooth diversity modules via their serial ports. As measurement results we obtained both the data rate of the Bluetooth connection and the magnitude of the received signal. Data rate measurements were performed by means of "HCI Toolbox" software made for BT device test via the host controller interface (HCI). For the field strength measurements the micro controller board was connected to a computer via its serial port. Then, the magnitude of the received field strength was observed, large numbers of samples were taken and stored via hyper-terminal. Finally the statistical distribution of the fluctuating field at the receiver side was derived using these data.

Representative application environments can be found e.g. in offices, living rooms, and laboratories. We performed a series of diversity demonstrator measurements in a laboratory/office room (7m x 13.5m x 3.25m), where different types of obstacles (working desks, computers, RF measurement devices, soldering equipment, wooden office cupboards and a metallic temperature test box) causing reflection, refraction and fading are located.

In order to investigate the performance of the BT diversity demonstrator in an industrial environment, a second series of data rate measurements was done in a factory for assembling of electronic devices (120m x 109m x 7m) (Fig. 8). Here many metallic obstacles such as reflow soldering machines, SMD mounting machines, work places for testing and mounting of electrical circuits, a closed depot, a closed office room and a closed break room can be found. During this measurements we confined our interest to angle

diversity.

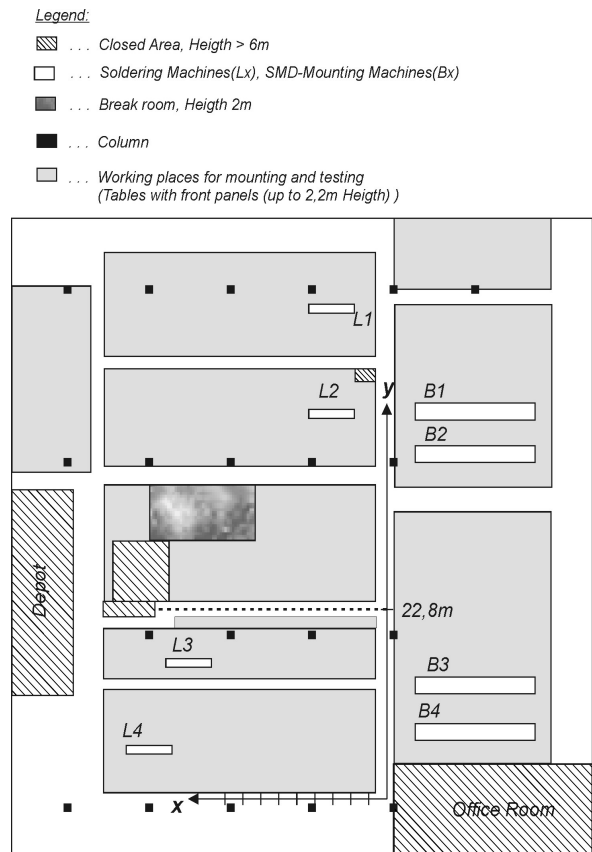


Figure 8: Sketch of the measurement scenario in the factory

### 4. Results

For the measurements in the laboratory/office room, we installed the transmitter in one corner of the room and performed data rate measurements for different positions of the receiver. The measurement results in the laboratory/office room for space and angle diversity are shown in Fig. 9 and Fig. 10 respectively.

Without diversity, data rate changed remarkably for different locations within a distance range of a few meters. As shown in both Fig. 9 and Fig. 10, a strong variation of data rate can be observed due to severe multipath propagation with an average coherence bandwidth of 7.4 MHz [4], [5]. Hopping across the whole 83.5 MHz bandwidth provides signal loss in many hops due to deep fading and shadowing almost independent from the geometric distance between transmitter and receiver.

Essential increase in data rate due to both space and angle diversity can be seen from the figures. Use of diversity overcame the multipath propagation effects and provided almost constant data rate throughout the room.

The cumulative distributions of the signal strength at an arbitrarily chosen point in the room, 6.4m apart from

the transmitter, are shown in Fig. 11. The average of the received power increased by 3dB for space diversity and by 8dB for angle diversity.

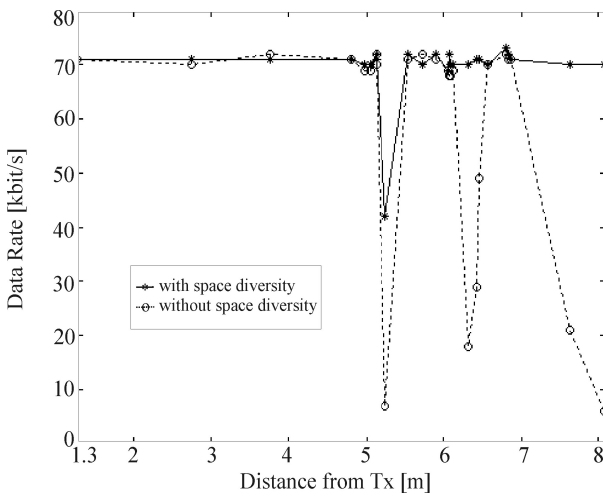


Figure 9: Data rate measurements in the laboratory/office room for space diversity mode

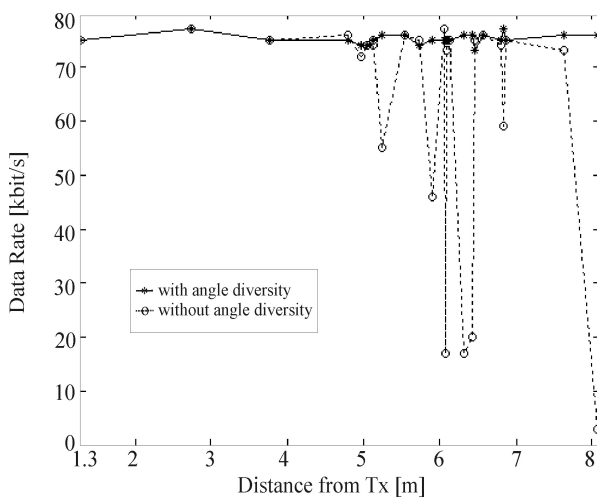


Figure 10: Data rate measurements in the laboratory/office room for angle diversity mode

The gain due to space diversity was remarkable in the power range from  $-71\text{dBm}$  to  $-85\text{dBm}$ . Here by space diversity 7dB maximum gain was achieved. The improvement by angle diversity was larger. A maximum gain of 12dB was observed.

In the factory the distance between transmitter and receiver was kept constant and the positions of transmitter and receiver were changed along parallel corridors 22.8m apart (Fig.8). The data rate measurement results are depicted in Fig. 12. The data rate had a strong variation at different positions along the corridor.

The use of angle diversity increased the data rate and

reduced the signal strength variations. The improvement achieved for angle diversity can be seen from Fig. 12. Angle diversity suppresses multipath and fading effects to a fairly large extent. The average data rate was 13kbit/s without diversity. It increased to 59kbit/s with angle diversity.

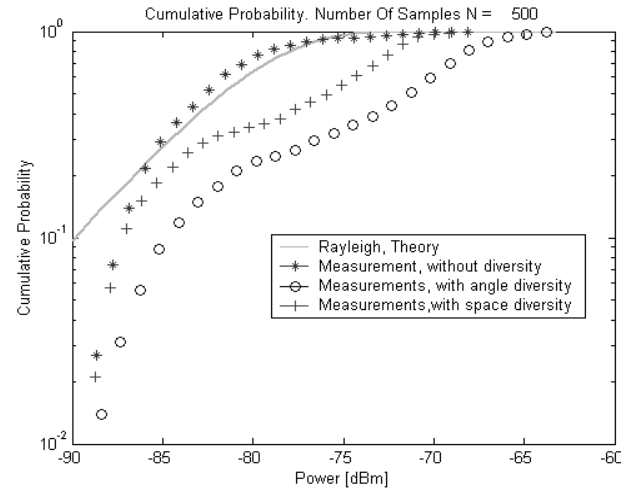


Figure 11: The comparison of the theoretical Rayleigh cumulative distribution and the measured data without diversity, with space and with angle diversity

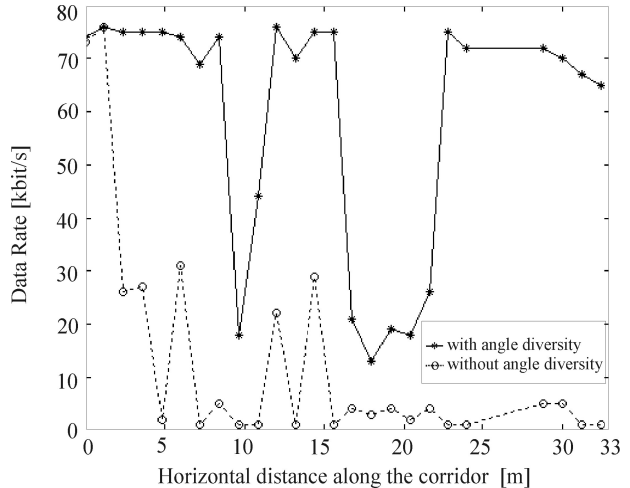


Figure 12: Data rate measurements along a corridor in the factory, angle diversity mode

## 5. Conclusion

In this paper, a Bluetooth antenna diversity demonstrator was presented. Measurements representing typical indoor scenarios were performed.

As a parameter with high significance for the availability and reliability of a data link, the data rate has been determined. Also, received power has been examined as a second means to quantify the gain due to diversity.

Space and angle diversity were examined. The performance of angle diversity was found to be significantly better than that of space diversity. It was shown that, the degradation in data rate due to impacts of the environment can be suppressed by antenna diversity to a large extent. Thus, significant improvement in the performance of Bluetooth communication links can be obtained.

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