Ultra-wideband High Data Rate Short Range Wireless Links

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Abstract-**High data rate wireless communications links use highly bandwidth efficient modulations to get the most from the limited spectrum available. Many of these schemes are complex, requiring large amounts of computation and hardware complexity to accomplish their tasks. This paper presents a method by which a high data rate, short-range, unlicensed wireless link is obtained using a modulation with low bandwidth efficiency to ensure that the radiated power spectral density is below maximum allowed levels. An experimental ultra-wideband system is described that is capable of transmitting up to 600 Mbps over distances of a few meters.**

INTRODUCTION

Many wireless technologies exist today to fill various communications needs. For example, one can find long-range systems (~10 km) with low data rates (~100 kbps), mid-range systems (~100 m – 1 km) with higher data rates (~1 Mbps) and local-area network systems with even higher rates (~10 Mbps). While systems that fall into these categories provide significant coverage options, there seems to be one genre missing: Short-range, extremely high data rate wireless communications. Such a system would be capable of greater than 100 Mbps at ranges of less than 5 m. A system such as this would also need to be inexpensive so that it could be used with a variety of consumer products.

Multimedia communications is one example application that would benefit from extremely high speed, short-range wireless links. For example, a digital video/still camera loaded with several hundred mega-bytes of images could wirelessly download its contents in a matter of seconds to a desktop PC. Computer data storage devices could also benefit from such a technology. A wireless storage device could enable a user to carry significant amounts of data from one location to the next and, upon arrival, transfer the data to another storage location in a matter of seconds using no wired media. Alternatively, one can imagine a compact personal digital assistant with limited internal data storage capability, but with the ability to wirelessly access large amounts of data while the user is in his or her office setting.

Keeping the previous applications in mind, the following system specifications embody what is seen as needed in such a high-rate, short-range wireless technology: 1) Data rates to 600 Mbps, 2) Short-range operation to 5 m, 3) Negligible interference presented to co-existing spectrum users. The work presented in this paper seeks to introduce theoretical and experimental foundations as a basis for understanding how this high-rate, short-range technology might be realized.

We will present calculations showing that operation within the limits specified in Title 47, Part 15 of the Code of Federal Regulations for intentional radiators is possible while presenting only negligible interference to co-existing users. An experimental apparatus—known as the high-rate, short-range (HRSR) system—has been constructed that is capable of transmitting up to 600 Mbps over distances of a few meters using simple Binary Phase Shift Keying (BPSK). Experimental results using this apparatus confirm calculated operation using a bit error-rate (BER) vs. transmitter-receiver (T-R) separation distance experiment as well as a BER vs. data rate experiment. Experiments confirm that interference with nearby PCS handsets and 802.11b wireless LANs is negligible.

THEORY OF OPERATION

Most of the wireless systems existing today are restricted to an allocated band by the FCC or other spectrum-granting organization. Even when using a moderately efficient modulation ($\eta \approx 1.5$)—where $\eta = \frac{R}{B}$, η is the bandwidth efficiency, R is the bit rate, and B is the bandwidth of the signal—an unlicensed 600 Mbps signal would not fit into an unlicensed ISM band until those found at the millimeter wave frequencies (e.g. ISM band located at 61.25 ± 0.250 GHz) [1]. Even as research is in progress to make use of these bands [2-4], components are not yet readily available and could require elevated development and integration costs. Components for use in the 2.45 GHz ISM band, comparatively, are more readily available and less expensive. However, the 80 MHz of bandwidth in the 2.45 GHz ISM band would require an extremely spectrally efficient modulation scheme to achieve 600 Mbps, which could also prove to be undesirably expensive in hardware and development costs. A possible solution to the bandwidth/band/cost tradeoff would be to share the spectrum in and around the IEEE S-band in a manner that does not cause harmful interference to co-existing spectrum tenants. A 600 Mbps BPSK modulated signal will have a 1.2 GHz null-to-null bandwidth, wide enough to overlap with several different services in and out of the ISM band. As any

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interference presented to these services and systems must be negligible, a quantified understanding of the maximum permitted interference is needed.

The Federal Communications Commission—in the Code of Federal Regulations, Title 47, Part 15, Subpart 209—specifies a limit on the maximum power that an unlicensed, intentional radiating device may use. Specifically, Subpart 209 indicates that for an intentional radiator operating above 960 MHz, the maximum electric field, $|E_{rms}|$, measured at a distance of 3 meters, denoted as d_{fcc}, from the source shall not exceed 500 microvolts per meter [5]. This maximum field specification yields a maximum power flux density, P_d [6]:

$$P_d = \frac{|E_{rms}|^2}{120\pi} \text{ [W/m}^2\text{]}. \tag{1}$$

Combining P_d and the effective area of the co-existing system's receive antenna, A_e, gives the power received by the co-existing system, P_{rc} [7]:

$$P_{rc} = P_d A_e = \frac{G_{rc}\lambda^2}{4\pi}\frac{|E_{rms}|^2}{120\pi} \text{ [W]}. \tag{2}$$

The maximum legal transmit power, P_{ts}^{max}, of the proposed system can be found by equating (2) and the Friis propagation equation (3) and solving for P_{ts}:

$$P_{rc} = \frac{P_{ts}G_{ts}G_{rc}\lambda^2}{(4\pi)^2 d^2} \text{ [W]}, \tag{3}$$

$$P_{ts}^{\max} = 4\pi\frac{P_d {d_{fcc}}^2}{G_{ts}} = \frac{|E_{rms}|^2 {d_{fcc}}^2}{30G_{ts}} \text{ [W]}. \tag{4}$$

P_{ts} and G_{ts} are the transmit power and transmit antenna gain of the HRSR system, respectively. The gain of the co-existing system's receive antenna is denoted by G_{rc}, λ is the wavelength of the carrier, and d is the distance between the HRSR transmitter and the receiver of the co-existing system.

Subpart 35 of FCC Part 15 specifies that for measurements made above 1000 MHz, a minimum resolution bandwidth, B_{res}, of 1 MHz shall be used in an average detector function to determine emission strengths [5]. Via the specified electric field limitation and the resolution bandwidth measurement requirement, a maximum transmit power spectral density, S_{max}, can be specified. The actual transmitted power spectral density, S_s, must be smaller than S_{max} to satisfy the legal constraints:

$$\eta\frac{P_{ts}}{R} = S_s \le S_{\max} = \frac{P_{ts}^{\max}}{B_{res}} \text{ [W/Hz]}, \tag{5}$$

which leads to

$$P_{ts} \le \frac{|E_{rms}|^2 {d_{fcc}}^2}{30G_{ts}}\frac{R}{\eta B_{res}} \text{ [W]}. \tag{6}$$

As long as the transmitted power of the HRSR system obeys (6), it will operate within the limits set forth by the FCC. However, it remains to be seen if this upper bound on transmit power will allow adequate signal to be received in order to obtain a specified bit error rate at the HRSR receiver. Therefore, a lower bound on transmit power is derived below.

The lower bound on the transmit power of the HRSR system is governed by the required minimum energy per bit, E_b^o, and the data rate, R. Since the system bit-error rate (BER) is a function of the received energy per bit, the product E_b^oR then specifies the minimum receiver power for the proposed system to achieve a specified BER. The minimum required energy per bit, E_b^o, can be found by relating the desired BER and the $\frac{E_b^0}{N_0}$ ratio, using the complementary error function (for coherent BPSK demodulation) [7]:

$$BER = \frac{1}{2}erfc\left(\frac{E_b^0}{N_0}\right). \tag{7}$$

For a specified BER of $5\cdot10^{-5}$, $\frac{E_b^0}{N_0} = 7.568$. The noise power spectral density, N_0, is then required to determine the minimum energy per bit and is given by:

$$N_0 = F_{sys}kT_o, \tag{8}$$

where F_{sys} is the system noise figure, k is Boltzman's constant ($1.38\cdot10^{-23}$ J/K), and T_o is the reference temperature (usually 290 K). The system noise figure, F_{sys}, is calculated using the following formula [7]:

$$F_{sys} = \frac{T_{ant}}{T_o} + F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \cdots, \tag{9}$$

where the component noise figures, F_1, F_2, F_3,..., are provided in the specifications of the components used in the HRSR system's receiver, in signal-flow order from antenna to receiver output. The component gain factors, G_1, G_2,..., are similarly obtained from specifications. The noise temperature of the antenna, T_{ant}, is assumed to be 290 K. For the experimental HRSR system, the system noise figure, F_{sys}, is calculated to be 7.80 dB. This yields a noise power spectral density of $2.409\cdot10^{-20}$ J. Multiplying the noise power spectral density, N_0, by $\frac{E_b^0}{N_0}$, the minimum energy per bit, E_b^o, is found to be $1.823 \cdot 10^{-19}$ J/bit.

As mentioned previously, the minimum received power for the HRSR system, P_{rs}, is

$$P_{rs} \geq E_b^o R \ \text{[W]}. \tag{10}$$

When (11) is combined with the Friis equation,

$$P_{rs} = \frac{P_{ts} G_{ts} G_{rs} \lambda^2}{(4\pi)^2 d^2} \ \text{[W]}, \tag{11}$$

the minimum transmit power is specified as,

$$P_{ts} \geq \frac{R E_b^o}{G_{ts} G_{rs}} \left(\frac{4\pi}{\lambda} \right)^2 d^2 \ \text{[W]}, \tag{12}$$

where G_{rs} is the gain of the proposed system's receiving antenna.

The minimum transmit power required to maintain a BER of $5 \cdot 10^{-5}$ is given in (12). A transmit power above this level will yield a link at the specified BER or better. It should be noted that this power level is calculated in a reflection-less environment. Operation in an environment containing multipath propagation will result in an increase in this minimum required power level.

Given an upper transmit bound (6)—specified by the FCC regulations, and a lower transmit bound (12)—specified by the required BER—a region of operation can be identified. Plotted over transmitter-receiver separation distance (T-R), this region of operation is shown in Fig. 1 (using the parameters shown in Table 1). If a specified operation point lies between the upper and lower bound curves, then a communications link that both operates within the limits of FCC Part 15 and maintains a specified BER will be realized. Effective isotropic radiated power (EIRP) in Fig. 1 equals the product $P_{ts}G_{ts}$.

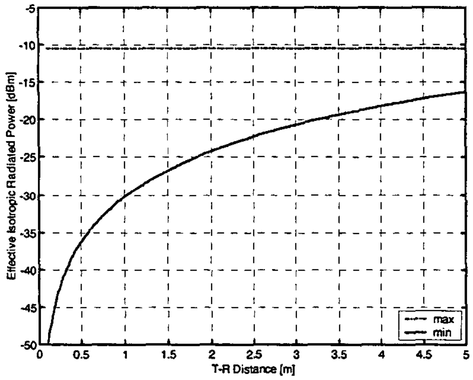

Fig. 1. FCC limited operation region with data rate of 600 Mbps.

TABLE I

PARAMETERS FOR OPERATING REGION CALCULATION

Symbol	Value	Parameter
G_{ts}	2.6 dBi	System transmit antenna gain
G_{rc}	3 dBi	Co-existing system rec. antenna gain
G_{rs}	2.6 dBi	System receive antenna gain
E_b^o	1.823e-19 J/bit	Minimum energy per bit
λ	c/3.0 GHz	Transmit wavelength
R	600 Mbps	System bit rate
S_l	1e-15 W/Hz	Max. power spectral density
η	0.5	Spectral efficiency

The results of the above theoretical discussions show that operation of the HRSR system is possible within the limits of the FCC regulations. Experimental results will now be examined to confirm operation, and to show that interference to co-existing spectrum users in negligible.

EXPERIMENTAL RESULTS

The experimental platform described herein provides confirmation of the theory derived in the previous section, and shows that the specifications presented are not mutually exclusive. Specifically, results will show that operation at distances up to 5 meters at 600 Mbps can exist while presenting only negligible interference to co-existing spectrum users. Measurements of BER across distance and system bit-rates will be presented, as well as interference characterizations of both the HRSR system on co-existing systems and those systems on the HRSR system.

The HRSR experimental platform is shown in Fig. 2. A bit error rate tester (BERT) is used to generate a pseudo-random noise sequence (PN) that BPSK modulates a carrier operating in the S-band. The transmitted carrier is received and amplified by a 34 dB low-noise amplifier, coherently demodulated, amplified one last time, and sent back to the BERT for data sequence comparison. The antennas used for the HRSR system are the discone style of antenna, shown in Fig. 3. This type of antenna provides a very wide bandwidth, required by the HRSR system's 1.2 GHz maximum operating null-to-null bandwidth. The discone's wide bandwidth also

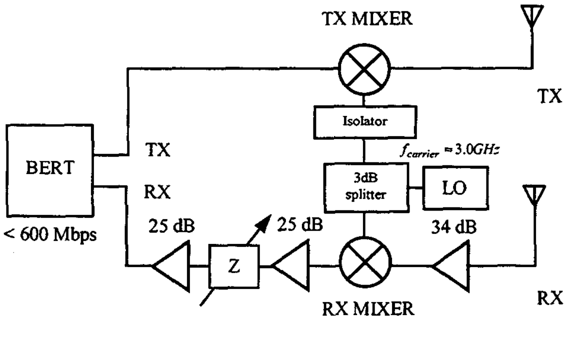

Fig. 2. Experimental setup of HRSR system.

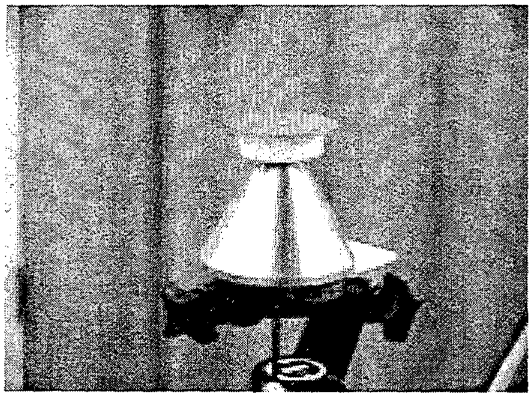

Fig. 3. Discone Antenna.

allows the carrier frequency to be translated across a large range (the operation range of this antenna is 1.0 GHz to 10.0 GHz). To measure the BER across a distance of 1-5m, the HRSR system's transmit power is adjusted so that it is in accordance with the FCC regulations (as calculated previously). Due to the large presence of multipath propagation in the indoor laboratory environment, comparative measurements are made using both the discone antennas, and a semi-ideal cable channel, attenuated to a level equivalent to the free-space path loss seen using the discones. Results are shown in Fig. 4. One can see that the cable channel performs significantly better than the discone channel, as expected due to the elimination of multipath effects. Furthermore, the cable-channel BER curve suggests the performance increase that could be derived from the use of a channel compensation technique, such as equalization. At a simulated distance of 5 m in the cable channel, the maximum separation distance specified for the HRSR system, a BER of $5.5 \cdot 10^{-8}$ was obtained—a good BER for most wireless systems.

The last curve shown in Fig. 4 shows the BER vs. distance measurement taken using directional log-periodic antennas. One can see a decrease in BER using these more directional antennas, suggesting that added directionality in system antenna design can help to mitigate the effects of multipath on the HRSR system. Reducing the effects of multipath will help to reduce inter-symbol interference, and thereby will increase BER performance. While such directionality can work to decrease the system BER, an increase in user's effort to align transmitters and receivers would be undesirable.

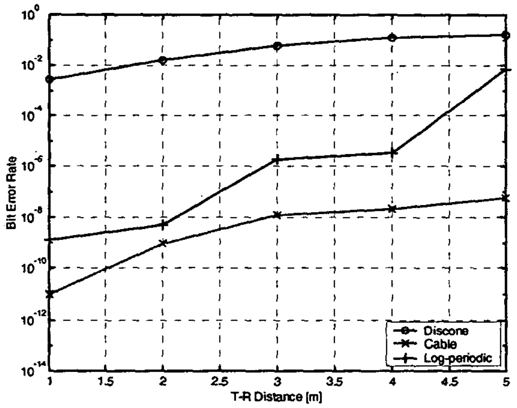

Fig. 4. BER vs. transmitter-receiver separation (T-R) distance measurements including log-periodic laboratory channel.

With the performance of the HRSR system characterized across distance, an examination of the HRSR system performance across system bit-rate is presented. Due to the presence of multipath propagation in the channel, nulls are created in the frequency-domain channel response. Such nulls will distort the signal of the HRSR system, if those nulls fall significantly in the transmitted HRSR spectrum. However, as the HRSR bit-rate is reduced, its spectrum becomes narrower, more able to fit in between such nulls.

In a fixed wireless channel, with the T-R distance fixed at 1 m, the HRSR system was operated at bit rates ranging from 10 Mbps to 600 Mbps. Each time the bit-rate was changed, the transmit power was also changed so that the HRSR system continues to conform to the FCC regulations. Additionally, the carrier of the HRSR system was translated until the BER was minimized. The results are shown in Fig. 5. One can see that the BER decreases as the bit-rate reduces from the full-scale bit rate of 600 Mbps, supporting the hypothesis that the HRSR spectrum is better able to fit in between channel nulls at lower bit rates. However, as the bit rate continues to decrease beyond 400 Mbps, the BER increases. The authors believe this anomaly is a limitation of the bit error rate tester, which can adjust the data/clock relative phase across 4 ns at maximum. For system bit rates on the order of 200 Mbps or greater, this adjustment is sufficient; however, for rates less than 200 Mbps, this adjustment range is insufficient and could lead to unsatisfactory clock synchronization.

Despite the anomaly observed below 200 Mbps, it is clear that the BER is affected by the bit-rate of the system. This knowledge could be particularly useful in an operational sense if combined with knowledge of the frequency-domain channel response. If the system were to autonomously measure the channel's response, it could intelligently place the transmitted spectrum where it performed the best. This ability to translate the spectrum in the frequency domain is facilitated by the previous FCC regulations analysis: Since the HRSR system complies with the power requirements as specified in Subpart 209, operation is possible at any frequency above 960 MHz. This method of channel compensation could likely be used in place of or in tandem with another channel compensation technique, such as coding or equalization to obtain enhanced system performance. With previous results showing that system performance is possible at the bit-rates, power levels and distances specified previously, an examination of the interference presented to co-existing spectrum users by the HRSR system is now presented. Interference was examined

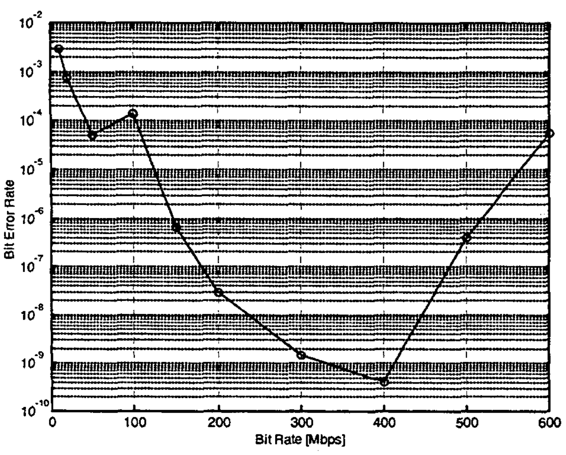

Fig. 5. BER vs. bit-rate measurements for laboratory/discone channel with T-R separation of 1 m.

on two systems: a WaveLAN (802.11b) link and a mobile phone. In the setup shown in Fig. 6, a WaveLAN link was established and baseline SNR measurements were taken (using the WaveLAN link utility) and found to be 48.5 dB and 53.0 dB for WaveLAN #1 and WaveLAN #2, respectively. Next, the HRSR system, set to operate in the 2.45 GHz ISM band at 600 Mbps, was enabled and a second set of WaveLAN SNR measurements were taken. The new WaveLAN SNR values were found to be 40.5 dB and 45.0 dB for WaveLAN #1 and WaveLAN #2, respectively, showing an average SNR degradation of 8.0 dB. However, neither WaveLAN device lost any messages, either before or after the HRSR system was enabled. Thus, even though the interference on WaveLAN is measurable, HRSR does not deteriorate WaveLAN performance, indicating that only negligible interference has occurred.

To examine the HRSR system interference on a mobile phone, a phone operating in the 1.9 GHz PCS band was positioned ~1.5 m from the transmit antenna of the HRSR system operating at 600 Mbps with a carrier frequency of ~1.9 GHz. Next, a group of test subjects proceeded to make 2 sets of 2 phone calls each and were then asked to rate which call in each set was clearer. This first set (C1 & C2) was a control set and the HRSR system was disabled. In the experimental set, the HRSR system was enabled for one call (E1), and disabled for the other (E2). In 12 different subject trials, 6 subjects found E1 to be clearer and 6 found E2 to be clearer; 5 subjects found C1 to be clearer and 7 found C2 to be clearer. These results show that no detectable difference can be noticed in the quality of the mobile phone call, indicating, again, that only negligible interference has taken place.

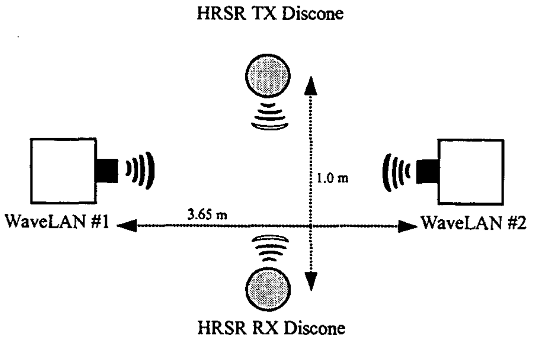

Fig. 6. WaveLAN/HRSR interference measurements experimental setup.

CONCLUSIONS

Theory presented in this paper shows that operation at 600 Mbps is possible within the limits set forth in Part 15 of the FCC regulations at short-range distances. Experimental results confirm theoretical calculations and provide experimental evidence that such operation is possible. Vulnerabilities to multipath propagation are identified, and the need for a form of multipath mitigation is established. A potential mitigation algorithm is discussed in which the HRSR (or similar) system would monitor the channel throughout time, and dynamically change both the system bit-rate and operation frequency in order to optimize performance. Interference on the co-existing 802.11b and PCS systems is measured and classified as negligible, satisfying the last of the specifications presented initially in this paper.

Future work on this topic could include an examination of a more realistic antenna design (the discone is bulky and not well mated to portable electronics applications), other multipath mitigation techniques (e.g. equalization, coding), and multiple access possibilities.

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