Silicon Wave™

PROCESSING GAIN MEASUREMENT RESULTS OF SILICON WAVE'S BLUETOOTH™ RADIO MODEM USING THE CW-JAMMING MARGIN METHOD

Abstract

This document provides results of the processing gain measurements for the Silicon Wave Bluetooth reference design platform when measured in accordance with the FCC's CW-jamming margin method. Because the page and inquiry modes of a Bluetooth system use a fixed access code across fewer than 75 frequencies, it is considered a hybrid system that employs a combination of both direct sequence and frequency hopping modulation techniques and therefore must achieve a processing gain of at least 17 dB from the combined techniques. The contribution to the processing gain caused by the three unique access codes used in this report is no more than 4 dB, and the calculated contribution from the frequency hopping part is 15 dB. The conclusion: the Silicon Wave Bluetooth reference design platform passes the processing gain test with a margin of at least 2 dB using a random (typical) access code and a margin of approximately 1 dB using a worst-case access code.

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Revision History

Revision	Date	Author	Description
R00A	June 14, 2001	M. Mester	Initial release.

1. INTRODUCTION

The FCC requires evidence of compliance to Section 15.247 (f) where a hybrid system that employs a combinations of both direct sequence and frequency hopping modulation techniques achieve a processing gain of at least 17 dB from the combined techniques. The FCC prefers that measured results be provided for the direct sequence part using a continuous wave (CW) jamming margin method. Silicon Wave has performed these measurements using the Silicon Wave Wireless Development System (WDS) that includes the reference design circuits used to implement its Bluetooth system. This white paper describes the method used to obtain the measured results using the WDS and the results that show the contribution of the direct sequence to processing gain is approximately 3 to 4 dB (depending on access code). Therefore, we conclude that the Silicon Wave Bluetooth system exceeds the required 17 dB processing gain with approximately 1 dB of margin using the worst-case access code.

The procedure followed in this white paper closely matches the method used by Ericsson outlined in their white paper titled "Processing Gain Measurement Results of Ericsson's Bluetooth Radio Module Using The CW-Jamming Margin Method" available from the FCC website located at http://www.fcc.gov/oet/fccid.

Section 2 (Description) details the CW-jamming method used to provide the measured results shown in Section 3 (Measured Results). A summary is provided in Section 4 (Conclusions).

2. DESCRIPTION

2.1 FCC Reference

The requirements for a Bluetooth transmitter in the acquisition mode operating as a hybrid transmitter are as follows. Hybrid spread spectrum transmitters are authorized under Section 15.247(f) of the Rules. The technical requirements in that Section require a minimum processing gain. The processing gain may be demonstrated as a combination of gain from the spreading/de-spreading function (using, for instance, a jamming margin test–see Section 15.247(e)(2)) and the gain from the hopping function, equal to 10log(number of hopping channels).

A copy of the processing gain measurement can be found at the end of the *Rulemaking Order for DSSS Transmitters*. This file is located at:
http://www.fcc.gov/Bureaus/Engineering_Technology/Orders/1997/fcc97114.txt

The relevant section is also recorded below for convenience:

> As measured using the CW jamming margin method: a signal generator is stepped in 50-kHz increments across the passband of the system, recording at each point the generator level required to produce the recommended bit error rate (BER). This level is the *jammer level*. The output power of the intentional radiator is measured at the same point. The jammer-to-signal ratio (J/S) is then calculated, discarding the worst 20% of the J/S data points. The lowest remaining J/S ratio is used to calculate the processing gain, as follows:
>
> Gp = (S/N)o + Mj + Lsys,
>
> where Gp = processing gain of the system, (S/N)o = signal to noise ratio required for the chosen BER, Mj = J/S ratio, and Lsys = system losses. Note that total losses in a system, including intentional radiator and receiver, should be assumed to be no more than 2 dB.

2.2 Bluetooth Access Code

The bit pattern of the access code is used to recover the data in a Bluetooth system. This de-spreading is accomplished by correlating the recovered bit stream with the known bit pattern of the access code. The success of the correlation determines whether the access code is valid. Invalid access codes result from bit errors in the bit stream that may cause the Bluetooth system to not recognize a valid access code or detect a valid access code from an invalid bit stream. Invalid access codes resulting from not recognizing a valid access code due to errors in the bit stream is referred to failed reject ratio (FRR) for the remainder of this white paper. BER can be replaced with FRR in the formula in section 2.1 to calculate the processing gain of the system. Valid access codes resulting from an invalid bit stream is referred to as the false alarm rate (FAR) is negligible when compared to the FFR, as shown below.

FRR can be calculated by determining a threshold for the number of bits correctly decoded in the 64-bit access code. The access code is considered valid if the number of bits without error in the 64-bit access code exceeds a pre-determined threshold (T). This threshold directly relates to the FRR and FAR. For a higher threshold T, the FRR decreases as the FAR increases.

Let P_{FA1} = Probability of false alarm for a single event.

p = Probability of bit error in the access code.

T = Sync word detection threshold. Access code is present if the number of correctly decoded symbols in the 64 bit sync word > T.

½ = Probability of a 1 or a 0.

Then,

$$P_{FA1} = \sum_{t=0}^{64-T-1} \binom{64}{t} p^{t} (1/2)^{64}, \text{ where } \binom{64}{t} = \frac{64!}{t!\,(64-t)!} \text{ and } 64 > t.$$

Furthermore, let:

P_{FA} = Probability of false alarm given multiple opportunities across a receive aperture.

M = Number of opportunities, nominally 84 (±10 μs plus 64 symbols).

Then,

$$P_{FA} = \sum_{m=1}^{M} \binom{M}{m} {P_{FA1}}^{m} (1 - P_{FA1})^{M-m}, \text{ where } \binom{M}{m} = \frac{M!}{m!\,(M-m)!} \text{ and } M > m.$$

Using the equations above and setting T = 59 (allowing 4 bits errors) and P_{BER} = 1.2e-2, FRR is 0.11% while the FAR is only 3.1e-12. Hence, for the purposes of the measurements made to calculate the processing gain, the FAR can be ignored.

An FRR of 0.1% was used to limit the test time required to make all the required measurements while still maintaining an acceptable degree of accuracy.

2.3 System Losses

The FCC assumes that the total losses in a system be no more than 2 dB in the calculation of Gp (processing gain). For the Silicon Wave Bluetooth reference design circuit, contributions to the system losses include:

1. **Frequency error and drift**. The Bluetooth specification allows for up to 75 kHz of initial frequency error and up to 25 kHz of frequency drift over a single-slot packet.

2. **Non-optimal sampling time**. The sampling time in a Bluetooth system is determined using the access code.

From 1 and 2 above, Silicon Wave expects to justify using 2 dB for the total system losses.

3. MEASURED RESULTS

3.1 Procedure

Silicon Wave developed a “test system” that was used in official Bluetooth qualifications for its module reference design because of the lack of available test equipment at the test labs during our qualification testing. The test system is a modified (via firmware) WDS approved by our BQB for use in testing during Bluetooth qualifications. Capable of establishing a connection with another WDS configured as a device under test (DUT), it also performs the necessary measurements required for Bluetooth qualification. Section 3.4 describes the equipment and setup used to make the FRR measurements in this document.

The FRR of the DUT is measured by configuring the DUT to continuously send single-slot DM1 type packets using a known access code at the normal Bluetooth system rate of 800 packets (with access codes) per second. The test system monitors the FRR and reports this to the screen. When the SNR is sufficiently high, the reported FRR will be 0.0%.

When a tone interferer is added to the system (CW jammer) the access code will be rejected when the threshold of allowed bit errors is exceeded. The correlator used in the Silicon Wave Bluetooth reference design circuit is programmed to allow up to 4 bits in error before an access code is declared invalid.

The first step is to measure the SNR required to obtain a FRR of 0.1%. This implies that only one access code is detected as invalid for every 1000 sent. At least 60 seconds is allowed before the FRR is recorded to provide enough accuracy to obtain a 0.1% FRR. Since 800 access codes are sent per second for 60 seconds, 48 missed access codes per minute corresponds to a 0.1% FRR $(800 \cdot 60 \cdot 0.001 = 48)$.

3.2 Signal to Noise Measurement

The output from the signal generator (AWG noise) is added to the output from the DUT (wanted signal) and sent to the test system. The signal generator output power is increased until the test system records a value of 0.1% FRR. The ratio of the wanted signal level to the noise level determines the SNR.

3.3 Jammer-to-Signal Measurement

Jammer-to-signal ratio (JSR) is determined by using the signal generator to produce an interfering tone (CW jammer), again added to the output from the DUT, and set to a level of 30 dB above the receiver sensitivity. As described in the FCC recommended procedure, the jammer is stepped in 50-kHz steps across the receiving channel. For each 50-kHz step, the CW jammer signal power is adjusted until the test system FRR reports 0.1%. The ratio of the CW jammer signal level to the wanted signal level determines the JSR for 0.1% FRR.

3.4 Test System Equipment List

Item	Function	Description	Manufacturer
1	Test system control	PC with test system software	Silicon Wave
2	DUT control	PC with DUT software	Silicon Wave
3	Test system power	Switch mode power supply	ENG Electronics
4	DUT power	Switch mode power supply	ENG Electronics
5	Test system	WDS configured as test system	Silicon Wave
6	DUT	WDS configured as DUT	Silicon Wave
7	CW jammer	ESG DP Series 4432B signal generator	HP
8	RF attenuator	HP8496A attenuator (0 to 110 dB) DC-4G	HP
9	RF attenuator	Model 910-20-11 attenuator (1 to 20 dB)	Weinschel Corp
10	RF combiner	Model 1580	Weinschel Corp
11	Directional coupler	Model 4242-20 0.5–2.0 GHz	Narda
12	Spectrum analyzer	R&S FSEM 20 Hz–26.5 GHz	Rohde & Schwarz

Table 1: Equipment List

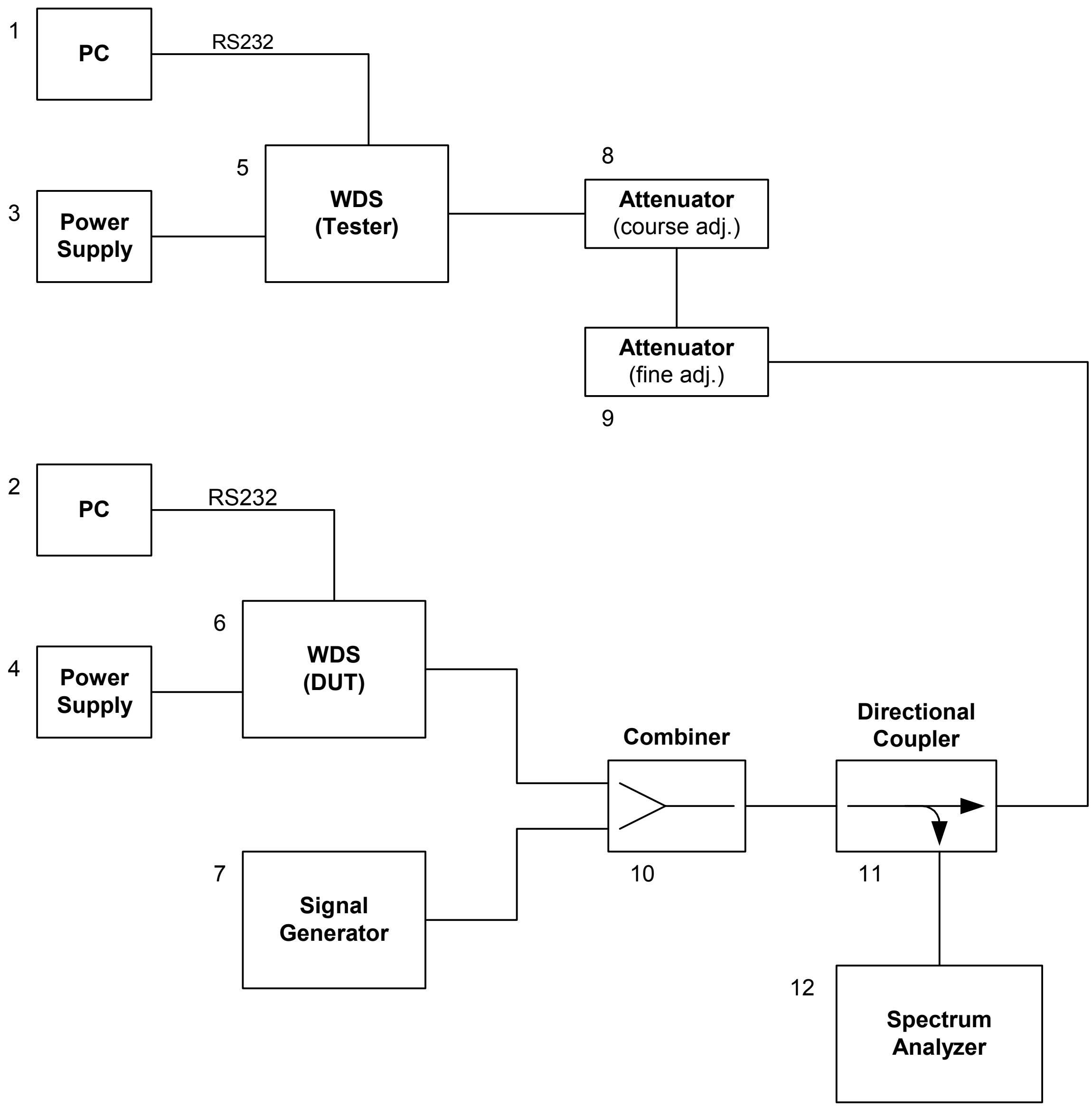

Figure 1: Test System Block Diagram

3.5 Results

The table below shows the measured results for the FRR using three uniquely different access codes (LAP = 000000, 9B415C, and FFFFFF). The highlighted measurements are the worst 20% of the J/S data points as allowed by the FCC. The processing gain (Gp) is calculated using the worst data point of the remaining measurements for each respective access code. Graphs and detailed calculations of each Gp are provided in the remaining sections.

Frequency offsets in kHz	LAP 000000	LAP 9B415C	LAP FFFFFF
-500	-17.2	-19.3	-18.0
-450	-18.3	-21.5	-20.1
-400	-18.0	-20.8	-19.5
-350	-17.7	-20.5	-19.2
-300	-15.3	-20.0	-18.0
-250	-13.5	-19.6	-17.2
-200	-11.6	-18.8	-16.3
-150	-9.6	-17.8	-15.5
-100	-7.3	-14.9	-15.0
-50	-5.4	-14.1	-14.2
0	-4.8	-13.2	-11.9
50	-8.0	-14.7	-12.3
100	-10.4	-18.9	-15.1
150	-11.8	-19.4	-16.7
200	-14.5	-20.0	-18.3
250	-16.3	-21.2	-18.8
300	-17.8	-19.5	-20.6
350	-18.6	-22.5	-19.5
400	-17.9	-20.3	-19.2
450	-17.2	-19.1	-18.9
500	-15.8	-18.5	-17.8
SNR	18.8	23.0	20.3
PG	3.0	4.5	3.1

Table 2: Failed Reject Ratio (FRR) Results by Access Code and Frequency Offset

3.5.1 Test Case 1

The SNR for the LAP of 000000 was measured to be 18.8 dB. Jammer offset (with respect to the wanted carrier frequency) as a function of JSR (to achieve a FRR of no more than 0.1%) is plotted below. In accordance with Section 2.1 on page 1 and as shown in the previous table, the jammer offset values of 350 kHz, 400 kHz, -400 kHz, and -450 kHz are discarded. The remaining worst data point is at is shown to be -17.8 dB at 300 kHz offset. This provides as processing gain of:

Gp = 18.8 - 17.8 + 2 = 3.0 dB

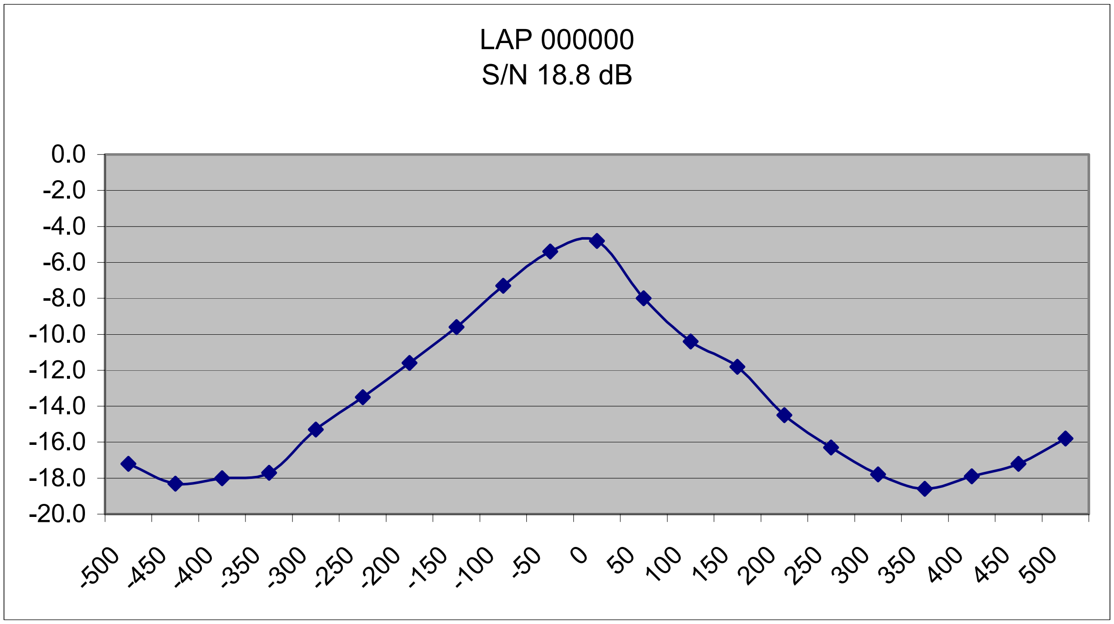

Figure 2: Jammer Offset and FRR for LAP of 000000

3.5.2 Test Case 2

The SNR for the LAP of FFFFFF was measured to be 20.3 dB. Jammer offset (with respect to the wanted carrier frequency) as a function of JSR (to achieve a FRR of no more than 0.1%) is plotted below. As shown in the previous table, the jammer offset values of 300 kHz, 350 kHz, -400 kHz, and -450 kHz are discarded. The remaining worst data point is at is shown to be -19.2 dB at -350 kHz offset. This provides as processing gain of:

Gp = 20.3 - 19.2 + 2 = 3.1 dB

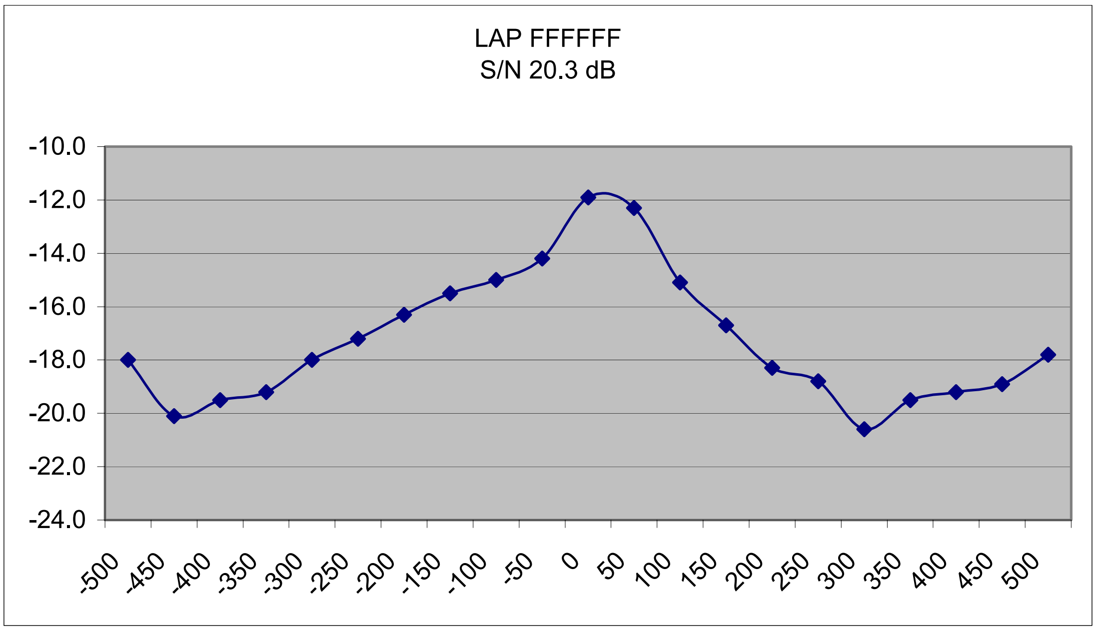

Figure 3: Jammer Offset and FRR for LAP of FFFFFF

3.5.3 Test Case 3

SNR for the LAP of 9B415C was measured to be 23.0 dB. Jammer offset (with respect to the wanted carrier frequency) as a function of JSR (to achieve a FRR of no more than 0.1%) is plotted below. As shown in the previous table, the Jammer offset values of 250 kHz, 350 kHz, -400 kHz, and -450 kHz are discarded. The remaining worst data point is at is shown to be -20.5 dB at -350 kHz offset. This provides as processing gain of:

Gp = 23.0 – 20.5 + 2 = 4.5 dB

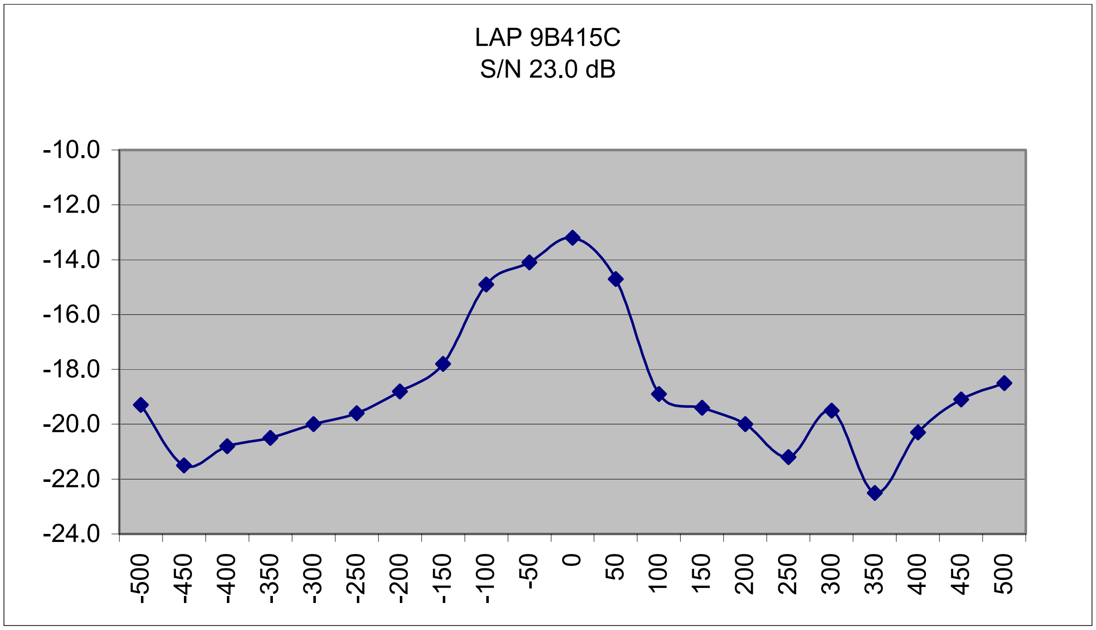

Figure 4: Jammer Offset and FRR for LAP of 9B415C

4. CONCLUSION

This white paper presents the results of processing gain measurements requested by the FCC to be compliant with the requirements imposed on a hybrid system that employs a combination of both direct sequence and frequency hopping modulation techniques. The FCC prefers that measured results be provided for the direct sequence part using a continuous wave (CW) jamming margin method. Measurements for uniquely different access codes were made at typical operating conditions for a Bluetooth system. The measured processing gain for these three access codes were very close and, in all three cases, exceeded the FCC requirements.

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