Bluetooth™ Manufacturing Test

A Guide to Getting Started

Application Note 1333-4

Introduction

***Note:* This application note is designed for electronic design/test engineers and managers who plan to manufacture products using *Bluetooth* wireless technology. It is addressed to a wide audience whose technical skills and knowledge may vary and therefore assumes no special knowledge of radio frequency (RF) techniques. For those who wish to explore the topics covered herein further, additional references are given in the Appendices.**

Bluetooth is an exciting new technology that offers wireless connectivity to an expanding array of electronic devices—computers, laptops, personal digital assistants (PDAs), digital cameras, cell phones, pagers, and wireless headsets. The use of *Bluetooth* technology has even been envisioned for home appliances like refrigerators and central air/heating systems. Cables and their connectors may soon be a thing of the past—for the first time, personal area networks can be created on an *ad hoc* or semi-permanent basis with no cables or connectors and only minimal network administration efforts.

Bluetooth frequencies occupy the 2.4 GHz ISM (Industrial, Scientific, and Medical) band, an unlicensed portion of the radio spectrum which is increasingly being filled by microwave ovens and other RF technologies, the most well-known being HomeRF and IEEE 802.11b. As the ISM band becomes more widely used, radio interference will no doubt increase. To counter this, *Bluetooth* technology uses several innovative techniques to provide stable linkages, among them cyclical redundancy encoding, re-transmission of data packets, and frequency hopping at up to 1600 times per second.

Originally created as a simple cable replacement, *Bluetooth* has become much more—users are increasingly seeking wireless capability in their workplaces and homes. *Bluetooth* is expected to be installed in nearly a billion appliances by the year 2005—it is unquestionably here to stay!

Building a test system for *Bluetooth* enabled products rolling down a manufacturing line would be easy if there were no design or test restrictions on the engineer. In the real world, however, we must deal with issues such as product size, throughput (which affects time-to-market), and cost. Addressing these issues and knowing the specific business strategies your company adopts will help you create a test system and plan that is efficient and cost-effective for your application.

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This application note will introduce you to the *Bluetooth* manufacturing environment, cite the many good reasons to test, discuss high-level business considerations, show you step-by-step how a *Bluetooth* test plan is created, and finally, profile other important manufacturing issues, such as yields, single- or multi-site testing, and test line limits (TLLs). The Appendices will give you detailed information on test methods and conditions, implications of *Bluetooth* radio design, important manufacturing issues, and descriptions of Agilent products for *Bluetooth* testing. By learning the principles and procedures herein and customizing them to your use, you will be able to create a test plan that is best suited to your company, product, and target market.

To help you in product development and testing, the *Bluetooth* Special Interest Group (SIG) maintains an official *Bluetooth* website, **www.bluetooth.com**, which is regularly updated with new and helpful information. Agilent's own *Bluetooth* website can be found at **www.agilent.com/find/bluetooth**, offering both technical information and product descriptions. A wide range of articles, press releases, application notes, and other information is also available on the website—and constantly growing.

We wish you the best of success in your *Bluetooth* efforts!

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INTRODUCTION

1. *BLUETOOTH* MANUFACTURING OVERVIEW

Bluetooth technology presents a major challenge to manufacturers. As a wireless medium, it contains RF complexities and problems which wired systems do not. It comes in many implementations, from wireless peripherals to local area networks to cellular phones. Moreover, market realities dictate that most *Bluetooth* devices must be manufactured at both high volume and low cost. All of these factors will clearly influence the approach engineers take not only to manufacturing, but also to test.

1.1
The Manufacturing Environment

Several methods for adding *Bluetooth* technology to a product are currently available: 1) creating the entire design, including *Bluetooth* capability, from the ground up, 2) buying *Bluetooth* ICs and designing them into the product, 3) installing pre-manufactured, pre-tested *Bluetooth* modules from other vendors, and 4) buying hardware which contains the *Bluetooth* capability and complementing your own design.

In terms of testing, much overlap occurs in these approaches. Whether you are manufacturing *Bluetooth* modules, larger subassemblies with *Bluetooth* capability, or fully-functional products for the end user, many of the same test issues will apply, including upstream verification and design/performance expectations. It is impossible to state simply which alternative you should choose—that will depend on many factors, such as economies of scale, availability of outside products, probability and type of process errors, and the level of RF expertise in your company.

1.2
High-volume Testing

For high-volume products, you should strongly consider automating your *Bluetooth* testing. This usually involves developing custom fixtures and a sophisticated materials-handling system, so that test connections can be made automatically. The primary enabler of high volume is short test time (i.e., high throughput), a reasonable goal being less than 10 seconds per manufactured unit. For low-volume products, you may be better served by choosing manual connection (with or without automated testing), where results come in a minute or two rather than a few seconds.

Another decision in high-volume operation is whether to test products in a single-site (one at a time) or multi-site (several at a time) fashion. If multi-site, the issue then arises of whether to test in sequence or in parallel. High-volume products are almost always tested in a multi-site fashion, with several devices under test (DUTs) being presented to the test station simultaneously. These could be tested in parallel, which calls for more complex fixtures, or sequentially, which reduces the test resources required but also means greater calibration and switching complexity. Yet another consideration is the type and diversity of products and fixtures the test station will encounter: Will different types and complexities of products be coming out in the future, putting more stress on the test environment, or will products remain largely the same?

In short, if the test system and test suite meet your time requirements and support your quality and profit goals, they can be considered successful.

1.3
Low Cost Orientation

In order to make a product, you need both materials and processes to put the product together (and ultimately to package it). *Bluetooth* products also incorporate a non-material content (bits) that govern the product's behavior.

The objective of making a product must be coordinated with that of making a profit. To do this, you should strive for an optimum efficiency at which per-product manufacturing cost falls well below the price of the product. Profit must take into account the costs of materials, manufacturing processes, tests, and customer support (returns, repairs, warranties, etc.).

A design or test engineer can do little about most of these, but minimizing manufacturing cost by minimizing *test* cost is a constant and primary goal—balanced, of course, by confidence in the product's quality.

1.4
Reasons to Test

Among the many compelling reasons to test *Bluetooth* products are the following:

1.4.1
Completing Product Functionality

Bluetooth products are sophisticated RF communication devices with complex software that drives their operation. One element of software is the ‘protocol stack,’ which is usually downloaded during manufacturing. Other ‘soft’ components may also be required for complete functionality—e.g., the unique *Bluetooth* identifier for each product. These need to be installed during the manufacturing process at a time when they are most supportive of the overall test approach.

1.4.2
Component or Subsystem Alignment

Bluetooth and other communication systems usually require some kind of component or subsystem alignment before operating as a complete unit—e.g., crystal tuning for output frequency accuracy, output power adjustment for battery longevity, power step accuracy to meet specifications and received signal strength calibration. All of these are part of dynamically adjusting the total RF link characteristics, without which proper unit operation in the field is impossible.

1.4.3
Performance Verification

At some point, *Bluetooth* system designs must be measured for compliance to the *Bluetooth* specification, although not every product will undergo this regimen in manufacturing (or perhaps only on a sample basis). Whenever it is done, however, *Bluetooth* specification testing should create a high level of confidence that the design will meet the *Bluetooth* standards. Among the parameters to measure are modulation accuracy, sensitivity, power output, and various spectrum measurements. Together with confidence in the overall quality (processes and materials), testing will help guarantee that the product is reliable, has the proper operating range, and will satisfy the customer.

1.4.4
Primary Use Case

Verifying that an electronic product operates at least approximately the way the customer will use it—i.e., the ‘primary use case’—may be critical to the ultimate success of the product. In the case of a *Bluetooth* enabled product, this means that it must join a piconet (2 to 8 *Bluetooth* devices linked together) in its normal role of master unit, slave unit, or both. It also means that it will be fully functional within that context, performing as expected. Only full functionality tests (many of which are non-*Bluetooth*) will be able to verify total performance.

1.4.5
Material Defect and Process Error Screening

Material defect and process error screening involves the identification of device failures due to aberrant performance because of shifts, long term drift in components, or process tolerance failures. While originating with the supplier of the components (and its particular process deviations), such defects are still the responsibility of the manufacturing test engineer—they must be addressed and eliminated.

1.4.6
Quality Assurance

Quality assurance testing is directed toward:

- Integrity and improvement of the manufacturing process, including data gathering and statistical process control
- Continued verification of correlated performances to confirm test plan assumptions or derive new correlations
- Ongoing verification of product conformance to the *Bluetooth* standard or FCC/ETSI regulations

The final four reasons for testing—performance verification, product functionality, material and process defects, and quality assurance—are drivers of the cost minimization process discussed above. The first two, completing product functionality and product alignment, are considered “test” processes in that they add value similar to that of material assembly processes. For example, defect screens should always be regarded as temporary because they represent material or processes which can be moved to a higher quality level. Quality assurance may take several forms, one being full sample testing, either on or off the production line, to ensure that all processes, materials, and designs are under control.

2. THE TEST PROCESS

2.1
Business Strategy and Approach Considerations

Strategic and business goals will affect everything done "downstream," so a thorough understanding of one's business environment and goals is prerequisite to creating a test system and processes. Each business environment is unique, so no attempt will be made to cover them in detail.

However, most design and test engineers will consider several common factors: product type, target market, material automation, test time, test budget, product volume, floor space, data handling for decision support, data handling for customer service, operator requirements (user interface, ergonomics, safety, etc.), company infrastructure, and business goals and objectives.

Each of these will place constraints on the test environment and processes—not to mention the test engineer! For example, if your company markets a popular consumer device for which high volume is necessary, test speed will be paramount. If equipment cost is critical, functionality vs. cost-of-test will be key. If credibility or reliable performance under stress is critical (as in government or military contracts), demonstrable performance under test will be the goal. The most common and important of these objectives will be speed and cost.

2.2
The Manufacturing Test Process

2.2.1
Overview

Figure 1 depicts the flow of the manufacturing test process at a very high level. It provides an excellent starting point to work through the complexities of the test process and move into more detail.

The illustration shows what happens at the factory level—material flows in, is connected, tested, verified (compared to a benchmark), then shipped out after test results are stored to a database. When we approach the test process this way, we have to consider not only the test plan and test station design—the initial goal—but also product delivery to the station, the method of interconnection to the station (not shown), spec comparison (test verdict), data storage, and product exit. In the diagram, the test plan is further expanded into product turn-on, alignment, and verification. Product alignment and measurement issues will be the chief drivers of overall test system design. Not shown but implied are test environment issues, such as test station design, software drivers, and fixtures.

2.2.2
Product Connection to Test System (Fixturing)

Since the test system contains the stimulus-and-response instrument(s) and support—cables, interfaces, switches, etc.—a mechanism is required to connect the DUT to the system. This is the test fixture. Depending on product complexity and functionality, a fixture can be very simple or as sophisticated as the test system itself! Two factors will dictate design of the fixture. The first is input/output (IO). IO connections are needed for power, control (e.g., digital interfaces), audio (if necessary) and RF signals (radiated or direct). The second factor is throughput, where the decision to test in multi-up fashion or not is key. Issues affecting this decision include whether switching is located in the test station or the fixture, speed of the connection, automatic vs. manual feed, isolation between IO lines, and fixture maintenance.

2.3
The *Bluetooth* Test Plan

As shown in Figure 1, the test plan consists of three main constituent parts. We also add result (spec) comparison below, since it is intimately connected with each test:

2.3.1
Turn-on and Product Initialization/ General Aliveness Checks

The point of the operation at which testing begins must be chosen at the outset, but may change over time depending on a product's performance. Typical concerns are passive power consumption, efficacy of control through the test interface, integrity of output lines for connectivity or activity, and minimal boot function to report results of a query. For example, each *Bluetooth* appliance/device will

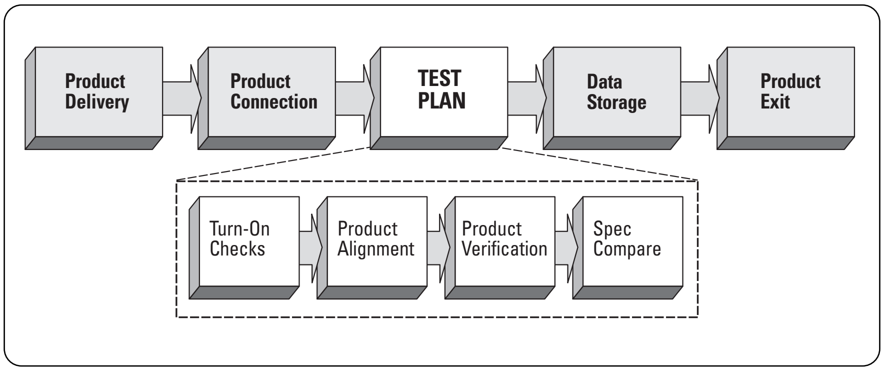


Figure 1: Overview of manufacturing test process.

have its own unique identifier, which will be needed somewhere in the manufacturing process (to simplify the test code, it is best to keep the identifier generic for as long as possible).

The protocol for a *Bluetooth* radio is usually downloaded during manufacture but may change over time for a given product or from one product to the next. The firmware may be monolithic (one file), or it may be split into baseband/link manager firmware and protocol stack, which have to do with the specific application. Verifying the protocol stack is not a manufacturing objective *per se,* but it must be loaded, and loaded correctly.

2.3.2 Product Alignment

Alignment is necessary for many devices, but varies from one vendor to the next. These differences need to be taken into account. Examples of alignment are crystal frequency adjustment, output power adjustment, received signal strength reading, IQ gain, quadrature and offset, and modulation index. Some of these may be tested at the integrated circuit (IC) level, but most of them cannot.

2.3.3
Product Verification

Product verification is the *single most important* aspect of the test suite—it will be your focus in whatever testing you undertake. Verification includes any parametric measurement which is critical to establishing and maintaining a link so that information can be transferred. Factors you should consider are which functional blocks in the *Bluetooth* radio are key to performance, mechanisms of possible failure, tests needed for confidence in the design, where in the frequency band or level they should be made, and which algorithms are best suited for manufacturing. When *Bluetooth* is merged into another design (e.g., a mobile phone), this list will expand.

2.3.4
Result Comparison

A test verdict is given when the numerical result of each test is compared to a pre-determined test line limit (TLL)—PASS or FAIL. The TLL is considered part of the test plan. It is established through an independent process, so it is discussed separately (Appendix D). The process of setting a TLL takes into account production statistics, desired yield, measurement uncertainties, and characteristics of design such as variation over temperature or humidity.

3. CREATING THE *BLUETOOTH* TEST PLAN

Customers will judge the performance of *Bluetooth* products based on factors such as range, transfer speed, and reliability of operation. “Just enough” test in manufacturing will ensure that their expectations are met. This section will identify a range of potential tests which can be used during manufacture, evaluate their importance, and discuss the optimum conditions for using them. Many of these tests can be implemented using *Bluetooth*’s “test mode,” which gives an engineer or operator the ability to initialize and control a DUT over the RF or host controller interface (HCI).

3.1
Factors in Creating a Test Plan

Until now, we have had primarily a factory perspective in describing the test process, but testing is only the culmination of a long development process which includes *all* aspects of the value chain. **Figure 2** depicts the factors which influence the creation and implementation of an effective test plan.

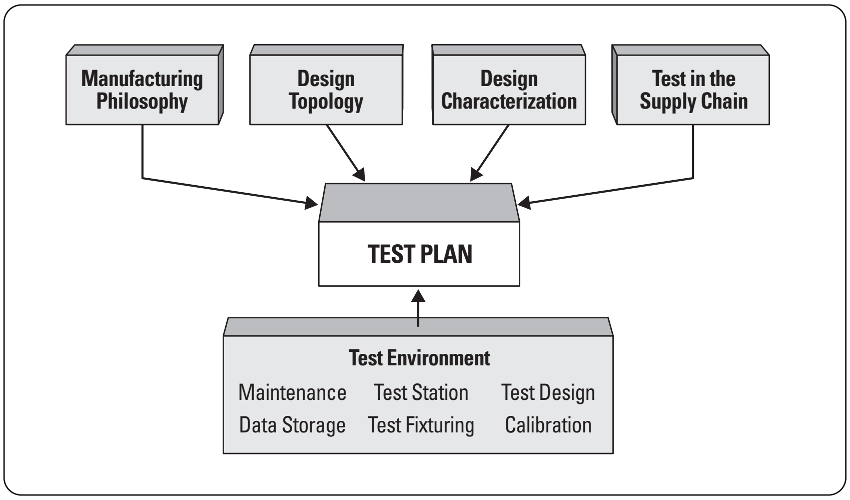


Figure 2: Factors in creating and implementing a *Bluetooth* test plan.

Figure 2 shows that the test plan is based on broad manufacturing philosophies and strategies, design topology, capabilities, limits, and idiosyncrasies of components, and correlations between parameters to be tested and test coverage further up the supply chain. When examined in detail, any product and test environment will reveal potential trade-offs in yield, measurement uncertainty, and throughput which support an overall desired result. Certain factors in the test environment—such as infrastructure, approach to fixturing, whether or not multiple DUT testing is used, and sampling rigor—will also affect the test plan. There may have to be some iterative experimentation to gain enough information to make decisions in these areas.

3.2
Identifying Tests for *Bluetooth*

STEP 1:
Survey Bluetooth SIG Tests

The *Bluetooth* Special Interest Group (SIG) has identified a large test suite (16 tests) to be used for qualification of *Bluetooth* products and devices (see *Bluetooth RF Test Specifications* in Appendix F). These are intended for qualification and are *not* prescribed for manufacturing test; however, many of them will be useful in manufacturing.

The SIG tests are listed in detail below. For each one, a priority (need to test) and a brief rationale are given. The priorities may be expanded into MUST test, SAMPLE test, and NEVER test if needed.

***Bluetooth* SIG Tests**

TEST	MFG. PRIORITY IN TEST	INSTRUMENTS
TRM/CA/01/C: **OUTPUT POWER** RATIONALE: Key parameter because of link budget, battery life, and incidence of failure. Alignment may occur at the same time, or in place of, measurement. Note: Spectrum Analyzer is used, but Power Meter or Test Set can suffice.	**HIGH**	**Spectrum Analyzer** or **Power Meter** or **Test Set**
TRM/CA/02/C: **POWER DENSITY** RATIONALE: Good characterization test to identify power output vs.frequency (channel number), but test time is high	**LOW**	**Spectrum Analyzer**
TRM/CA/03/C: **POWER CONTROL** RATIONALE: Useful in designs or cases where battery life is maximized through dynamic level control. Standard specifies performance attributes. Although chip used may support this, the actual product may not have this as a requirement. Alignment may occur at the same time, or in place of, measurement. Note: Spectrum Analyzer is used but Power Meter or Test Set can suffice.	**HIGH**	**Spectrum Analyzer** or **Power Meter** or **Test Set**
TRM/CA/04/C: **OUTPUT SPECTRUM (FREQUENCY RANGE)** RATIONALE: As described in standard, this is ~10 seconds of test time. Mechanisms for failure might be common to failing items for -20 dB Spectrum Test as well as Modulation Index.	**LOW**	**Spectrum Analyzer**
TRM/CA/05/C: **OUTPUT SPECTRUM (20 dB Bandwidth)** RATIONALE: Output radiated spectrum is an issue of regulatory compliance. May be adequately covered by chip testing. As described, ~10 seconds of test time. Correlation with modulation characteristics is possible. Good for quality control.	**HIGH/MED**	**Spectrum Analyzer**
TRM/CA/06/C: **OUTPUT SPECTRUM (Adj Ch Power)** RATIONALE: Test time is very long. Spot checks may be done instead. Good for quality control.	**LOW**	**Spectrum Analyzer**
TRM/CA/07/C: **MODULATION CHARACTERISTICS (Index)** RATIONALE: Verifies waveform quality, in particular the fm index (beta), and is a critical information transfer parameter. Can be included in the alignment section in some designs. Too low modulation index may result in poor sensitivity; too high indicates excessive spectrum spread.	**HIGH**	**Spectrum Analyzer** or **Test Set**
TRM/CA/08/C: **INITIAL CARRIER FREQ TOLERANCE (Accuracy)** RATIONALE: A parameter which confirms transmit burst function and synthesizer settling. Some designs are more susceptible to failure than others because of design topology. Could be used as coarse check for crystal accuracy.	**HIGH**	**Spectrum Analyzer** or **Test Set**
TRM/CA/09/C: **CARRIER FREQUENCY DRIFT** RATIONALE: Some designs are more susceptible to failure than others because of design topology. Demodulation variability can lead to interoperability problems.	**HIGH**	**Spectrum Analyzer** or **Test Set**

STEP 2:
Prioritize SIG Tests for Manufacturing

The previous list includes priority ranking and a rationale for each test in its importance to manufacturing. **Table 1** (pg. 10) summarizes and highlights the priorities and various types of equipment which can be used in the tests. By examining all of them, we'll note that high-priority tests can all be covered by a *Bluetooth* RF test set, such as the Agilent E1852B. A primary goal of low cost would commend a *Bluetooth* test set as the major component of the test system.

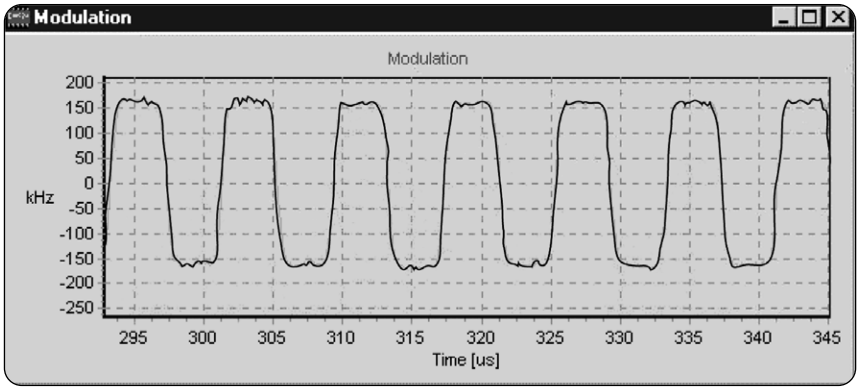


Figure 3: Agilent E1852B display, showing a modulation analysis (Frequency vs. Time) from SIG Test TRM/CA/07/C.

Bluetooth* SIG Tests** ***(cont.)

TEST	MFG. PRIORITY IN TEST	INSTRUMENTS
TRC/CA/01/C: **OUT OF BAND SPURIOUS EMISSIONS** RATIONALE: Obvious large test time involved. Spot check suspect areas such as for upconversion spurs or subharmonics. Should be considered a design issue, not a manufacturing one.	**LOW**	**Spectrum Analyzer**
RCV/CA/01/C: **SENSITIVITY (SINGLE SLOT PACKETS)** RATIONALE: Key parameter for information transfer, i.e., the link budget. Limited by noise in the environment (silicon fab and adjacent circuits). Impairment checking is excessive in production testing and probably not good for process control unless only one impairment is selected. Characterization required to find appropriate sensitivity level at which to test. Select the number of bits appropriate and impairment mode if design so warrants.	**HIGH**	**Special Setups** or **Test Set**
RCV/CA/02/C: **SENSITIVITY (MULTI-SLOT PACKETS)** RATIONALE: Key parameter for information transfer, i.e., the link budget. Determine if there is significant performance difference from single-slot sensitivity. If not, do one or the other. Multi-slot can be the worst of the two.	**HIGH**	**Special Setups** or **Test Set**
RCV/CA/03/C: **CARRIER/INTERFERENCE PERFORMANCE** RATIONALE: Try to keep out of manufacturing if possible because complexity and cost rise due to summing network and extra equipment. Margin may be hard to achieve with tight specification (14 dB). Similar measurement as in sensitivity test.	**MEDIUM**	**Interfering Sig. Source** and **Test Set**
RCV/CA/04/C: **BLOCKING PERFORMANCE** RATIONALE: Performance is likely guaranteed by design or characterized and shown to be within acceptable limits. Complexity and cost rise due to summing network and extra equipment. Similar measurement as in sensitivity test.	**LOW**	**Interfering Sig. Source** and **Test Set**
RCV/CA/05/C: **INTERMODULATION CHARACTERISTICS** RATIONALE: Performance is likely guaranteed by design or characterized and shown to be within acceptable limits. Complexity and cost rise due to summing network and extra equipment. Similar measurement as in sensitivity test.	**LOW**	**Interfering Sig. Source** and **Test Set**
RCV/CA/06/C: **MAXIMUM USABLE LEVEL** RATIONALE: Design may be insensitive to overloading. 'Primary use case' of product may never present an overload problem. However, some radios do not function properly if too close to each other.	**MEDIUM**	**Test Set**
OPTIONAL TEST: **RECEIVED SIGNAL STRENGTH INDICATOR** RATIONALE: Key parameter for information transfer, i.e., the link budget, especially in more active use cases where proximity of radio can change. Important for battery life.	**HIGH**	**Test Set** or **Signal Source**

Table 1:
Tests Ranked by Importance to Manufacturing and Types of Test Equipment Used

		Instruments				
TEST NAME	PRIORITY	POWER METER	SPECTRUM ANALYZER	TEST SET	SIGNAL SOURCE	SPECIAL SETUPS
OUTPUT POWER	**HIGH**	X	X	X		
POWER CONTROL	**HIGH**	X	X	X		
MODULATION CHARACTERISTICS (Index)	**HIGH**		X	X		
INITIAL CARRIER FREQUENCY TOLERANCE (Accuracy)	**HIGH**		X	X		
CARRIER FREQUENCY DRIFT	**HIGH**		X	X		
SENSITIVITY (Single-slot Packets)	**HIGH**			X		X
SENSITIVITY (Multi-slot Packets)	**HIGH**			X		X
RECEIVED SIGNAL STRENGTH INDICATOR (optional)	**HIGH**			X	X	
MAXIMUM USABLE LEVEL	**MEDIUM**			X	X	
CARRIER/INTERFERENCE PERFORMANCE	**MEDIUM**			X	X	
OUTPUT SPECTRUM (-20 dB Bandwidth)	**MEDIUM**		X			
OUTPUT SPECTRUM (Frequency Range)	**LOW**		X			
OUTPUT SPECTRUM (Adjacent Channel Power)	**LOW**		X			
OUT OF BAND SPURIOUS EMISSIONS	**LOW**		X			
BLOCKING PERFORMANCE	**LOW**			X	X	
INTERMODULATION CHARACTERISTICS	**LOW**			X	X	
POWER DENSITY	**LOW**		X			

The tests in the SIG *Bluetooth RF Test Specifications* formally specify the conditions (frequency, power, sensitivity, etc.) under which parametric measurements should be performed, conditions which are not necessarily appropriate for manufacturing test. The right conditions for *your* product will be those that guarantee your desired level of confidence in the product's design and take into account typical performance statistics. For example, frequencies for any parameter measured should be chosen for expected *worst-case* performance—e.g., sensitivity should be verified at a channel where characterization shows design sensitivity to be the least. This is not to penalize the design, but to minimize test time and maximize confidence.

Additionally, the modes and methods of tests can be different from those specified. You should use whichever tests accomplish the same or similar goals. Nothing dictates that a huge 1.6 Million bits be used in a bit error rate (BER) sensitivity test for production, or that you perform a 10-second -20 dB Spectrum test! The test engineer must know the device and test objectives, then develop speedy but effective test processes to cover function and performance. These tests will result in a better understanding of the relationships between various parameters, whose test line limits may then be changed, followed by new tests, and so on. Several test methods are discussed in detail in Appendix A.

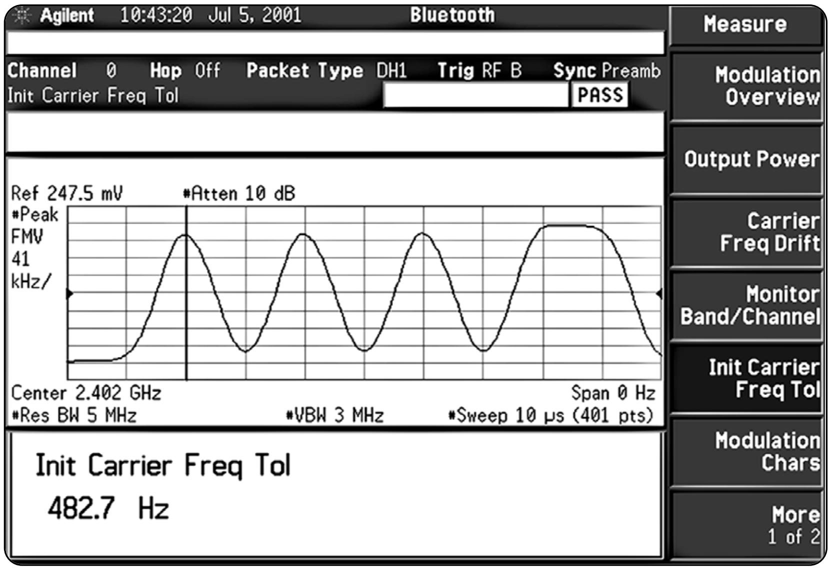
STEP 3:
List Other Candidate Tests

In addition to *Bluetooth* SIG tests, you should consider a variety of other tests. Which of these you choose will be dictated largely by chipset design, the confidence you place in your manufacturing processes, and the device's susceptibility to failure. For example, current draw in various modes is important if your device is battery-operated (in which case a battery emulator will become a key test component).

Examples of such tests are presented in **Table 2.**

Table 2:
Additional Candidate Tests

TYPE OF TEST	EXAMPLES	DESCRIPTION
TURN-ON TESTS	IO Control Test	Respond Over USB/Digital Interface
	FW Download	Protocol Stack Download
	UID	Unique Address Loading
	Current Drain	Power Supply Loading
ALIGNMENT	Transmit Power Cal	Calibrate Output Level
	Frequency Adjustment	Crystal Trim
	RSSI Cal	Calibrate Input Level Measurement
	IQ Modulator Cal	IQ Modulator Balancing
OTHER PERFORMANCE TESTS	Transmit Mask	Power Ramp Characteristics
	Frequency Mask	Frequency Settling Characteristics
	Current vs. Operating State	Current Drain in Various States of Operation
FUNCTIONAL TESTS	Depends on product	Example: File Transfer on LAN Access Point, Audio Tests on Headset
CUSTOM TESTS	Depends on product and test philosophy	Example: Transmitted Spurs in Band



Agilent 10:43:20 Jul 5, 2001 Bluetooth

Channel 0 Hop Off Packet Type DH1 Trig RF B Sync Preamb

Init Carrier Freq Tol PASS

Ref 247.5 mV #Atten 10 dB

#Peak FMV 41 kHz/

Center 2.402 GHz Span 0 Hz

#Res BW 5 MHz #VBW 3 MHz #Sweep 10 µs (401 pts)

Init Carrier Freq Tol

482.7 Hz

Figure 4: Agilent ESA Spectrum Analyzer measuring Initial Carrier Frequency Tolerance.

STEP 4:

Summarize Tests

What we have done up to this point is to survey potential tests for *Bluetooth*, both SIG and others. **Table 3** represents the bulk of these tests narrowed into a possible set of choices. For *Bluetooth* SIG tests, only those designated high or medium priority were included.

Table 3:
Superset of Possible *Bluetooth* Tests

TYPE OF TEST	POSSIBLE TESTS
INITIAL TURN-ON	Respond Over Interface
	Firmware Download
	Unique Address Installation
	Power Checks–Nominal Current
ALIGNMENT	Power Calibration
	Crystal Tuning
	Received Signal Strength Indicator (RSSI)
	Modulation Index Characteristics
PERFORMANCE	Output Power
	Power Control
	Modulation Characteristics (Index)
	Initial Carrier Frequency Tolerance (Accuracy)
	Carrier/Interference Performance
	-20 dB Spectrum
	Carrier Frequency Drift
	Sensitivity (Single-slot Packets)
	Sensitivity (Multi-slot Packets)
	Received Signal Strength Indicator (Optional)
	Current vs. Operational Mode
	Frequency Settling
	Power vs. Time
FUNCTIONAL	File Transfer, Audio Checks, etc.

These tests may or may not be done at the same location. Because of the variations in turn-on and functional testing, the wide range of measurement issues, and differing philosophies of approach, only alignment and performance testing will be treated further.

Alignment can be done simultaneously (or nearly so) with verification, since the same equipment, test commands, and setup procedures are used. For example, from the SIG tests listed earlier, we could combine alignment of output power with measurement of output power. Similarly, the alignment of modulation index and received signal strength indicator (RSSI) could be done with the modulation characteristics and RSSI performance tests, respectively. In most cases, sensitivity tests need not be duplicated at all. So our *Bluetooth* test suite could now look like **Table 4**.

Table 4:
Streamlined Choices Focusing on Alignment and Performance Tests

TEST AREA	POSSIBLE TESTS
ALIGNMENT	Crystal Tuning
PERFORMANCE	Power Output: Alignment and Power Verification
	Power Control
	Modulation Characteristics: Alignment and Verification
	20 dB Bandwidth
	Initial Carrier Frequency Tolerance (Accuracy)
	Carrier Frequency Drift
	Sensitivity (Multi-slot Packets)
	RSSI alignment and Received Strength Indicator Operation
	Carrier/Interference
	Current vs. Operational Mode
	Frequency Settling
	Power vs. Time or Pulse Shape

STEP 5:

Evaluate Tests for the Particular Bluetooth Radio

Once a general set of tests is identified, we must consider tests which depend on the topology of the particular *Bluetooth* radio used. Depending on its design, the radio can virtually guarantee that certain tests need not be done, or it can necessitate additional tests because of its unique susceptibilities—or both! A detailed analysis of the implications of *Bluetooth* radio topology is given in Appendix B.

To gain detailed knowledge of the *Bluetooth* radio, we must characterize it using a number of important criteria:

- **Distribution Analysis:** Performance of one or several parameters over an appropriate sample size
- **Temperature Variability:** Determination of how one or several parameters change over temperature
- **Humidity Variability:** Determination of how one or several parameters change over humidity
- **Covariance Analysis:** Examination of relationships between several measured results on given units
- **Characteristic Curves of Performance:** Identification of the general characteristic of a parameter vs. a given range of conditions of test—for example, transmit power vs. frequency

Temperature and humidity characterizations are usually not performed in the production environment or considered part of a *Bluetooth* manufacturing strategy. They are more likely to be used as elements in setting test line limits (TLLs), which are considered in detail in Appendix D. Distribution analysis is key to determining variability of design, identifying which parameters can have a high spread in performance, and which can cause failures. Covariance analysis is a more sophisticated process which seeks to find relationships between different measures of performance in order to focus on either the most fundamental or most cost-effective method of screening potential errors.

The clearest benefit of these tests to the production process is the identification of characteristic curves. When these are found, they will yield insight into how best to test the product. A few examples are given in Appendix C.

STEP 6:
Evaluate Upstream Testing

We now consider tests which can be eliminated ‘downstream’ because of testing further up the supply chain. This requires a survey of components, their sources, and tests done on them. If you are making a final appliance, this will include not only the IC manufacturer’s tests, but those of the *Bluetooth* module manufacturer (if applicable).

Full *Bluetooth* radio implementations can consist of as little as one or two ICs and a number of off-chip components such as crystals and capacitors. Test coverage at the IC level should definitely be considered in creating a test plan for the final appliance. Upstream test coverage of the IC will vary from vendor to vendor due to coverage philosophy, test capability, access points for test, and state of radio completion. In most cases, the last factor will be critical, since crystals, capacitors, and protocol stack have not been added yet. Hence the SIG test coverage available at the IC level will be limited to tests *not* affected by these components.

As seen in **Table 5**, opposite page, many of the *Bluetooth* tests can be performed at the IC level. The Agilent 93000 SOC Series with RF Measurement Suite, for example, provides a high-volume manufacturing test solution for radio modem and baseband controller ICs. These tests are identified in Step 8. For more information, see Agilent Product Notes 5988-4260EN and 5988-4261EN.

Using all of the tests discussed so far, we can now begin to create an overall test coverage matrix, as shown in Table 5. Listed in the first column are tests which can be done to verify product performance; all other tests can be done upstream. In this case, we will assume that only upstream IC testing applies. In actuality, each individual case will be different.

STEP 7:
Refine Tests to Final Choices

The “Alignment Required” column represents areas which require alignment, so these tests must be done downstream regardless of what IC or module testing is done earlier. However, a certain amount of upstream coverage of power output and modulation characteristics has been done, so testing in these areas may be reduced. For example, instead of testing at three or more frequencies, you may decide to test at only one or two. Also, note the excellent test coverage under “Other SIG Tests” provided by the equipment manufacturer. Since reducing cost (by reducing test time) is a key goal in high-

Table 5:
Overall Bluetooth Test Matrix

			Upstream Tests in the Supply Chain IC Test															
		ALIGNMENT REQUIRED	OUTPUT POWER VS. FREQUENCY	OUTPUT POWER CONTROL	-20 DB BANDWIDTH	SPURIOUS SIGNAL GENERATION: IB	SPURIOUS SIGNAL GENERATION: OB	FREQUENCY SETTLING TIME	MOD CHAR: MODULATION INDEX	MOD CHAR: INITIAL FREQ. ACCURACY	MOD CHAR: FREQUENCY DRIFT	Rx INTERMODULATION DISTORTATION	Rx INTERFERENCE: BLOCKING	Rx INTERFERENCE: CO-CHANNEL	Rx INTERFERENCE: ADJ CHANNEL	Rx DYNAMIC RANGE: SENSITIVITY	Rx DYNAMIC RANGE: MAX INPUT POWER	DIGITAL AND DC TESTS
Alignment Tests	Crystal Tuning	Y																
High Priority Performance Tests	Power Output	Y	X															
	Power Control	N		X														
	Modulation Characteristics	Y			X				X									
	Initial Carrier Frequency	N						X		X								
	Carrier Frequency Drift	N									X							
	Sensitivity	N														X		
	RSSI	Y																
	Battery Current vs. Operational Mode	N																X
	Frequency Settling	N						X										
	Pulse Shape	N						X										
	Output Spectrum -20dB Bandwidth	N			X													
Other SIG Tests	Maximum Usable Level	N															X	
	Output Spectrum Freq Range	N					X											
	Output Spectrum Adj Ch Power	N				X												
	Out of Band Spurious Emissions	N					X											
	Carrier/Interference Performance	N												X				
	Blocking Performance	N											X					
	Intermodulation Characteristics	N										X			X			
	Power Density	N			X													

volume manufacturing, you should avoid redundant testing whenever possible. Therefore, we will focus mainly on the "High Priority Performance Tests" in our test plan.

Initial frequency tolerance is a function of crystal accuracy. Because the crystal is off-chip, this cannot be measured by IC testing and therefore will need to be tested in the full appliance. On the other hand, frequency drift does not depend on absolute frequency—it is solely a function of internal phase-lock circuitry, which is tested at the IC level—so it is not required at the appliance level. Note that the received signal strength indicator (RSSI) can be tested at the IC level; however, this test requires alignment, so it will also need to be done at the appliance level.

Finally, though tested as an IC parameter, sensitivity is not considered to have high correlation because it depends on so many other factors—environmental noise, the antenna, soldering defects, etc. Hence it needs to be verified at the appliance level. Should these factors turn out to have acceptable tolerances, you may decide to hold the radio modem to tighter requirements at the IC level and do less sensitivity testing yourself.

Using our assumptions about tests and processes so far, we can identify the following for our test suite:

- Crystal Trim
- Power Alignment and Performance
- Modulation Index
- Initial Frequency Tolerance
- Sensitivity
- Received Signal Strength Indicator
- Battery Current vs. Operational Mode

Caution: Although this is a reduced set of tests, it is a always wise to keep all tests surveyed on your master list, since later analysis may uncover correlations that would have changed your decision. It is also important to note that when the IC test has been taken into account, it becomes part of the overall *composite test* process and can therefore be used to minimize downstream failures.

STEP 8:
Determine the Test Sequence

Because test is a substantial part of manufacturing cost, it is best to test a DUT for the *highest likelihood of failure first,* so time is not wasted on further testing—the unit can then be discarded or recycled for repair. This rule assumes that it is ready for such precise discrimination—i.e., that all alignments have been made. With *Bluetooth* enabled devices, the rule can be expanded (especially if testing and alignment are done at one location): *All alignment should be done for the next test with the highest likelihood of failure.*

For example, you might determine that battery current tests fail most often, followed by sensitivity and frequency drift. If no calibrations are required for current and sensitivity tests, you could choose the following order:

- Crystal Tuning (needed to ensure accurate results)
- Battery Current Waveform
- Sensitivity
- Modulation Index Alignment and Verification (drift measurement uses modulation parameters)
- Initial Frequency Tolerance and Drift
- Power Alignment and Verification (contributes to the current in transmit mode)
- Received Signal Strength Indicator

Another consideration for the test sequence is the ability to get several results at once using a common output or input signal. For example, it is possible to verify power and modulation characteristics at the same time if a *Bluetooth* test set is used, since it provides these transmitter measurements simultaneously.

STEP 9:
Determine Test Methods and Conditions

In general, the conditions of test are determined by design performance characteristics of the product being tested, as exemplified by *Bluetooth* radio testing (see Appendix C). Hence we are transcending the *Bluetooth* SIG's recommendation for the certification test process, which in most cases is to pick high, medium, and low points to measure. We will not only change the conditions at which to test, but the test methods as well, to suit our individual objectives in manufacturing. Appendix A deals with some of these in detail.

With the exception of alignment, testing in production is not so much a matter of *search* as it is of *point comparison*—that is, the measurement is taken and the result checked against a given limit for PASS or FAIL. Searches are appropriate only for characterization or quality assurance processes.

The tests we have identified so far can now expanded to include test methods and conditions. Appendix A provides more detail.

1. Crystal Tuning/Trim

Measurement:
Frequency Count

Process:
Measure reference frequency and adjust trim mechanism to obtain reading within an acceptable range. This will be set as tight as possible (±1ppm) because it will directly affect frequency accuracy (initial carrier frequency tolerance [ICFT] test).

Measurement Method:
Use the frequency counter function of a *Bluetooth* test set, standard frequency counter, or spectrum analyzer. This instrument should either have great absolute accuracy or be driven by a reference standard.

2. Sensitivity Testing

Measurement:
BER

Process:
Establish loopback by paging DUT using a *Bluetooth* test set (in this case, the Agilent E1852B) in test mode and initiating the *Bluetooth* radio using appropriate host controller interface (HCI) commands through the application program interface (API) for the chip used. Set the transmit level to DUT, taking into account fixture losses; level is determined through the characterization process. Measure BER and compare to specification. Repeat for all test frequencies selected if more than one is appropriate.

Measurement Method:
Select number of bits and test line limit for testing that is appropriate to speed desired (see Appendix A). Set up the test set for testing with selected number of bits. Trigger a BER measurement on the test set.

3. Modulation Characteristics

Measurement:
Frequency deviation over prescribed number of bits in payload.

Process:
Establish loopback by paging the DUT using the test set in test mode and initiating the *Bluetooth* radio using appropriate HCI commands through the API for the chip used. Initiate DUT transmission of appropriate bit sequences (01010101 or 00001111) in the payload. Using nominal transmit level to DUT from the test set, trigger on the DUT transmission and determine the deviation for the bit sequence. Repeat for all test frequencies selected if more than one is appropriate.

Measurement Method:
Use a *Bluetooth* instrument designed specifically for this measurement, such as a *Bluetooth* test set or a spectrum analyzer. Trigger F0 and F1 measurements.

4. Initial Center Frequency Tolerance and Drift

Measurement:
Integrated deviation over a specified number of bits as prescribed in the *Bluetooth RF Test Specification.* This is performed over first bits of a packet (preamble) for the initial frequency measurement. The drift measurement compares 10 bit integrations within the packet, as well as the preamble result.

Process:
Establish loopback by paging the DUT using the test set in test mode and initiating the *Bluetooth* radio using appropriate HCI commands through the API for the chip used. Initiate DUT transmission bit sequence (01010101) in the payload. Using nominal transmit level to DUT from the test set, trigger on the DUT transmission and determine the ICFT and drift for the bit sequence. Repeat for all test frequencies if more than one is appropriate.

Measurement Method:
Use a *Bluetooth* instrument designed specifically for this, such as the Agilent E1852B or the ESA Spectrum Analyzer. Trigger ICFT and drift measurements and compare result to test line limit. ICFT is by definition a noisy measurement as it is determined from 4 bits (4 µs). Average for degree or margin of stability desired.

5. Transmit Power Alignment and Verification

Measurement:
RF Power

Process:
The DUT can be measured or calibrated for power in a number of ways, depending on the capabilities of the IC and on whether calibration vs. verification is being performed. In its simplest form, a *Bluetooth* loopback condition in test mode is set up with a *Bluetooth* test set, the DUT is set up to send a pseudorandom (PN9) sequence, and the power is measured. Loss factors of the system (frequency dependent) are applied and the resultant is compared to the test line limit. Another possible process is that DUT output is connected directly to a power meter for an alignment, and a search is invoked which sets DUT output level with a digital to analog converter (DAC), using the chip vendor's device API. In such cases, a verification process may or may not occur. If so, it is best done under normal *Bluetooth* operating conditions (i.e., test mode).

Measurement Method:
A power meter can be used for highest accuracy or a *Bluetooth* test set to trigger average or peak power measurements. Method depends on how DUT is set up to transmit—e.g., *Bluetooth* packet vs. continuous PN9.

6. Battery Current vs. Operational Mode

Measurement:
Current vs. time to find peak, average, or duty cycle.

Process:
Current is measured over a period of time appropriate for the mode being verified. These modes can be directly set using the API for the chip being used.

Measurement Method:
Using a DC power supply with high dynamic range current measuring capabilities, such as the Agilent 66319B/D or 66321B/D, trigger appropriate current measurement (peak and/or average) when *Bluetooth* radio enters mode of interest. This is detailed in Appendix A.

7. Received Signal Strength Indicator

Measurement:
None

Process:
This may be an alignment or a verification. The specifications in *Bluetooth* are rather wide, so in a verification, a signal is applied to the DUT and a query made through the API regarding the path loss to the DUT. As there are three ranges, three different levels will be applied in this process.

Measurement Method:
Use an instrument which can provide a *Bluetooth* signal, such as a *Bluetooth* test set or signal generator, and set it to the appropriate level, such as that for the DUT. The resultant is a returned value of range determined by input level or directly by measured level.

4. OTHER IMPORTANT MANUFACTURING TEST ISSUES

With all tests now chosen and their methods and conditions listed, we have greatly narrowed the list of test equipment needed. Building the test station would be the next logical step. A *caveat* here, however: The yields and margins required for your particular manufacturing process may not be supported by the equipment initially selected. Other, more precise instrumentation may be necessary, such as a power meter for level measurements or a counter for measuring frequency. A test engineer will need to investigate thoroughly the test methods, measurement uncertainties, system calibration requirements, etc. of the system in order to determine the exact equipment needed.

Earlier in this document, we referred to single-site and multi-site testing as a decision that must be made at some point. Single-site is clearly the simplest option; however, handling and throughput will be limited if the decision is made to go with a multi-site approach, and a host of other decisions must be made. These will involve the means of test station address as well as test station design. The interfacing of the DUT(s) to the station will be through a test fixture or test jig, which can be as simple as throughline wires or cables or can be quite complex, with sophisticated circuitry to enable efficient testing. The station design must also address sequential or parallel testing of multiple DUTs, trading off switching complexity with instrument cost and speed.

The Agilent 93000 Test System, for example, takes advantage of tests which require a stimulus by splitting the signal into four paths to address all the DUTs and thus eliminates the cost of three other signal generators. Creative sequencing of tests will also save cost. For example, a DUT could be stimulated by a signal for a receiver test, while another DUT is undergoing a transmitter verification—using multiple system resources simultaneously. Such a design can increase throughput; however, it will be dependent on other tests which use transmit and receive test time.

Finally, there is the issue of determining test line limits (TLLs) to obtain desirable production margins. This process will affect your yields and/or product quality. For each test, the test engineer will need to determine the mean and standard deviation performance of the design, as well the measurement uncertainty of the test—which includes both instrument *and* fixture. To do this requires creating a distribution model, which can be used to determine what the expected yields will be for a given margin.

These topics are discussed in greater detail in Appendix D.

5. SUMMARY

In this application note, we have covered the subject of *Bluetooth* manufacturing test from a high level down to detailed testing. We began with a description of the *Bluetooth* manufacturing environment, then cited the necessity for low cost-of-test when creating new *Bluetooth* enabled products. We emphasized the many positive reasons to test, among them the assurance of complete product functionality and maintenance of quality standards.

We described and visualized the manufacturing test process, beginning with high-level business and strategic considerations which ultimately influence and shape it. We showed step-by-step how a *Bluetooth* test plan is derived, describing each phase in some detail. We covered other important manufacturing issues, such as parallel testing, DUT fixturing, and test result determination. For those who are interested, more detail on these and related topics can be found in the Appendices.

No single document can cover every contingency in every manufacturing scenario (especially in complex, interference-prone areas like *Bluetooth*). However, we strongly believe that by learning the principles and procedures in this document—and customizing them to your own use—you will be able to create a test plan that is appropriate and cost-effective for your company, your product, and your market.

We encourage you to visit our *Bluetooth* website, **www.agilent. com/find/bluetooth** for up-to-date information on a variety of *Bluetooth* topics. To contact Agilent, see the information on the back cover of this document. We will be happy to help you with any of your *Bluetooth* questions, concerns, or challenges.

APPENDIX A:

Test Methods and Conditions Detailed

A.1.
Sensitivity Measurement

Sensitivity is the measure of a receiver's ability to convert faint signals accurately. In digital modulation radio systems, this accuracy is expressed as bit error rate (BER)—the percentage of bits received which are in error. The BER for a system is always stated as a maximum value at a given level. The *Bluetooth* specification is .1% BER at -70 dBm applied to the receive port. This is generally done using a clean signal, since it is a measure of signal-to-noise; however, the *Bluetooth* specifications stipulate an impaired signal for certification. It is therefore likely that the level for .1% BER will be less with a clean signal. The improvement is about 2 dB.

BER is by definition a probabilistic measurement, so you should be careful in setting guidelines for it, avoiding measurements that do not achieve the desired confidence level. This means that you should stipulate the time period or number of bits over which the measurement is valid and the confidence level you believe is appropriate. In **Figure 5**, a 95% confidence BER curve is shown. Note that even at a million bits, a 95% confidence is achieved in a .1% BER only when the BER is at or below .095%. From this graph, you can choose the operating point desired. Pick the number of bits (which directly affects the time of the measurement) and determine the maximum BER that can be read from a test. For example, 23,000 bits can be used if the reading is less than .07% to determine a .1% spec with 95% confidence. The time saving can be significant: For DH5 packet BER testing, the time to test would be less than 100 ms vs. approximately 4 seconds for 1.6 million bits!

Sensitivity can be verified in several ways using an established radio link, or not. Both can be valid approaches. In the case of no link, a modulated source (which can include packetization) is applied at the chosen level, with the BER result fed back through special subroutines in a vendor's control software. This usually employs pseudorandom data, which can be evaluated simply (e.g., PN9 in the *Bluetooth* specification).

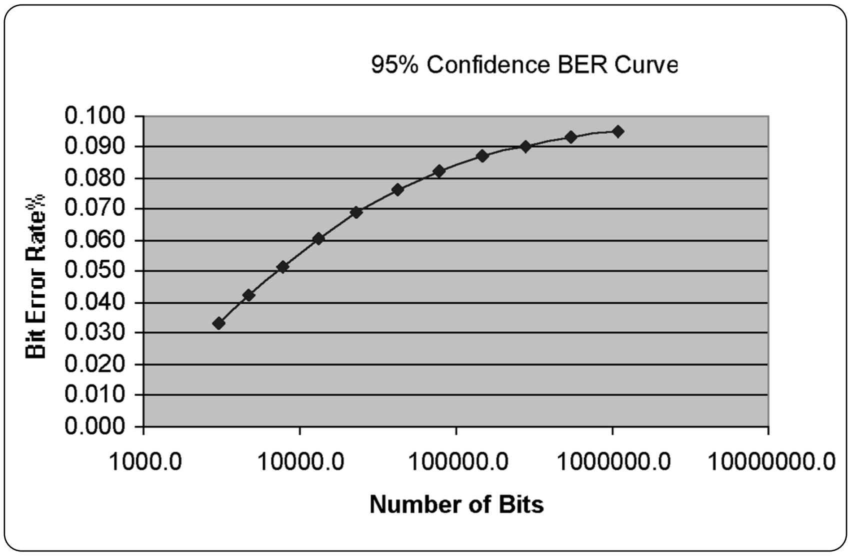


Figure 5: A BER curve depicting a 95% confidence level.

While this can be effective, the benefits of 'live' links are difficult to overstate, so you should strongly consider measuring sensitivity over a simulated link. To perform the measurement, you need the following:

- A *Bluetooth* radio
- *Bluetooth* transmitter power control
- A means to measure transmitted data from the DUT for bit error rate

These capabilities can be found in many one-box testers, such as the Agilent E1852B *Bluetooth* Test Set.

A.2
Current vs. Operating Mode

Operating time is a critical parameter for every *Bluetooth* battery-powered device, and thus is a major purchase criterion for the user. Reduction of power consumption will continue to be a top priority for earlier *Bluetooth* designs. Even now, consideration is being given to partitioning the *Bluetooth* chip design so that portions of it can be shut down as a function of operating state; however, these methods are largely proprietary. Hence battery current drain measurements are essential, both for verification of design and control as well as efficacy of the silicon manufacturing process. The wide range of battery drain—which extends to very low levels (tens to hundreds of µA)—plus the pulsed nature of *Bluetooth* transmissions, dictate that a current measuring instrument have a large dynamic range and be capable of measuring measure peak, root mean square (RMS), and dc current.

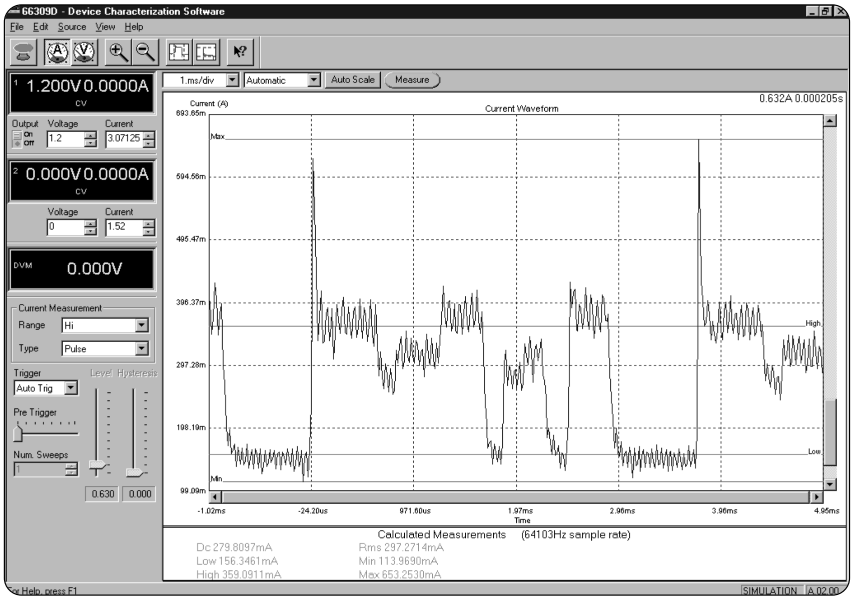
A.2.1
Battery Current Drain vs. Operating State

Bluetooth devices have many operating states, each providing a certain capability with a corresponding power drain. This enhances their performance as networked devices, while also optimizing their battery-operating time. Key states need to be identified in order to assure specified operating time as well as minimizing testing. Due to the diversity of *Bluetooth* applications, key operating states can vary widely, making their precise identification difficult. The states depend both on the application of the particular device and its dynamic range of operation. IC vendors will sometimes offer direct control of circuit blocks over an HCI, primarily for confirmation of the silicon manufacturing process and not necessarily for standard function. The key operating states fall into four broad categories:

A.2.2
Operating States and Current Drain Characteristics

- **Active Call State Operation**

  The highest level of power consumption takes place when the *Bluetooth* device is linked and actively communicating with the host network. It uses a digital transmission format that draws pulse current, its period being a multiple of 1.25 ms. An active call state current drain is illustrated in **Figure 6.**



1 1.200V 0.0000A CV
Output: ○ On ● Off
Voltage: 1.2
Current: 3.07125

2 0.000V 0.0000A CV
Voltage: 0
Current: 1.52

DVM 0.000V

Current Measurement
Range: Hi
Type: Pulse

Trigger: Auto Trig
Pre Trigger
Num. Sweeps: 1
Level: 0.630
Hysteresis: 0.000

1.ms/div
Automatic

Calculated Measurements (64103Hz sample rate)
Dc 279.8097mA
Low 156.3461mA
High 359.0911mA
Rms 297.2714mA
Min 113.9690mA
Max 653.2530mA

Figure 6: Example *Bluetooth* device active call current drain waveform.

- **Standby/Scan State Operation**

  When not networked, a *Bluetooth* device acting as a slave will operate on standby at an intermediate to low power level. During each 1.28s scan, the device wakes up for 11.25 ms to receive and check for inquiries and pages. This results in a low-repetition-rate, low-duty-cycle pulsed drain. A *Bluetooth* device acting as a master on standby actively transmits paging and inquiry calls, similar to the active call state. Devices can often be put into this mode by direct control over the HCI.

- **Low-power Modes of Operation**

  During periods of inactivity, the *Bluetooth* device can be placed into low-power modes of operation—such as PARK, HOLD, and SNIFF—for extended time periods. To conserve power, the device enters a sleep mode, drawing as little as tens to hundreds of µA of current.

- **Battery Charging (when applicable):**

  For high-power *Bluetooth* devices with rechargeable batteries, the charging function is typically built in. For proper control of charging, current and voltage are measured and calibrated during manufacturing test.

A.2.3
Battery Current Drain Measurements and Needs for *Bluetooth* Test

Key modes of operation dictate specialized test system needs, which are summarized in **Table 6.**

Table 6:
Summary of *Bluetooth* Battery Current Drain Measurements and Needs for Manufacturing

***BLUETOOTH* OPERATION & TEST PARAMETER**	**TEST RATIONALE**	**MEASUREMENT SYSTEM NEEDS**
ACTIVE CALL & PAGE/INQUIRY STATES		
dc current	Assures meeting specified battery operating time when active.	Handles high crest factors.
		Accuracy of 0.5% or better for dc average level (typically from tens of mA to A).
		Integration system suited for fast and accurate averaging over ms waveform periods.
high-level current **peak current**	Assures against premature battery minimum voltage shutdown.	Incorporates high-speed pulse signal, high and peak level detect circuitry, or algorithms.
STANDBY/SCAN STATES		
dc current	Assures meeting specified battery operating time when in standby.	Handles very high crest factors.
		Accuracy of 0.5% or better for average levels (typically from single to tens of mA).
		Integration system suited for fast and accurate averaging over long (>1 s) waveform periods.
LOW POWER AND OFF MODES		
dc current	Assures against unexpected battery drain when off.	A low-level current measurement range, around 10 mA.
	Detects latent defects in components and assembly.	10 µA or better measurement accuracy.
		Suitable measurement delay and integration periods for stable value.
BATTERY CHARGING MODE		
dc voltage **dc current**	Part of device calibration. Assure of proper battery charging function	Measures charge (negative) current (typically up to 1 A) with 0.5% or better accuracy.
		Measures charge voltage (typically up to 9 V) with 0.2% or better accuracy.
		Additionally: The dc source should double as a constant voltage load and sink charging current to emulate a charging battery.
		A second dc source to provide charging current.

A.3
-20 dB Spectrum Measurement

The -20 dBm spectrum measurement is a readily identifiable *Bluetooth* trademark. The specification stipulates that the -20 dB bandwidth be less than 1 MHz wide when modulating pseudo-random data. The specification suggests a test method which takes in excess of 10 seconds per carrier frequency. It also specifies that the loopback test mode be employed during measurement. Both of these conditions can be waived for manufacturing. A spectrum analyzer can capture the waveform of a continuously modulated transmitter in less than 100 ms. If the *Bluetooth* IC vendor provides this capability in its control software, you can measure a representative spectrum of the transmitter. The resultant will be different from the SIG measurement because of the lack of randomness of the data; however, transmitter physics are exactly the same—e.g., the modulation index, distortion mechanisms, etc.

APPENDIX B: Implications of *Bluetooth* Radio Topology

B.1 Radio Topology

Topology refers to how a particular design accomplishes the requirements imposed upon it. Every *Bluetooth* radio design differs according to the chip vendor. Different approaches to design can make you immune to some pitfalls and susceptible to others.

The design in **Figure 7** incorporates phase-locked loop signal synthesis, common oscillator for transmitter and receiver, transmitter level control (perhaps with a power amplifier for extended range), switched front end, and filter at the antenna. For the receive path, we might use a low-noise amplifier for extended range (or Class 1 operation), standard downconversion to an intermediate frequency (IF) with FM demodulation through a tuned circuit, and an RSSI circuit which may or may not be active, depending on the application.

Compare this with the more sophisticated digital design of **Figure 8.**

In this design, frequency synthesis is also common for transmitter and receiver; however, this time it is IQ modulated. Other features, such as the antenna switch and filter, are similar except that the filter is assumed to be off-chip. Note also that the receiver does not make use of an analog discriminator.

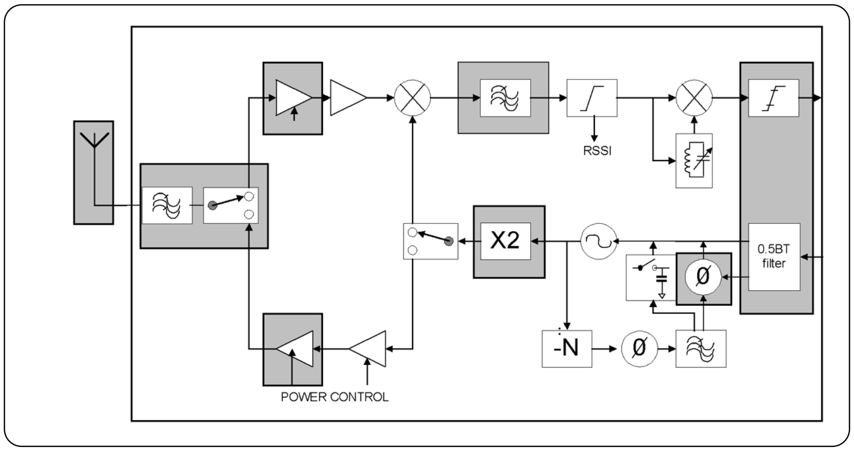


Figure 7: ***Bluetooth*** **RF radio design using analog techniques.**

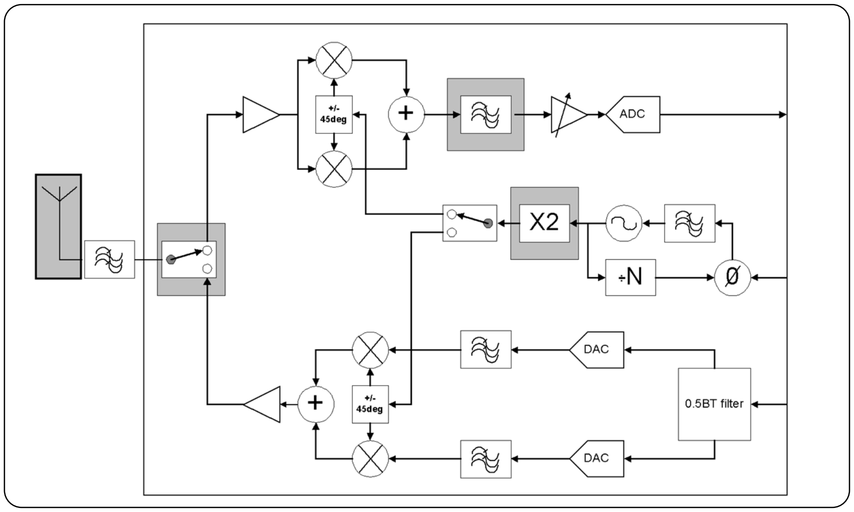
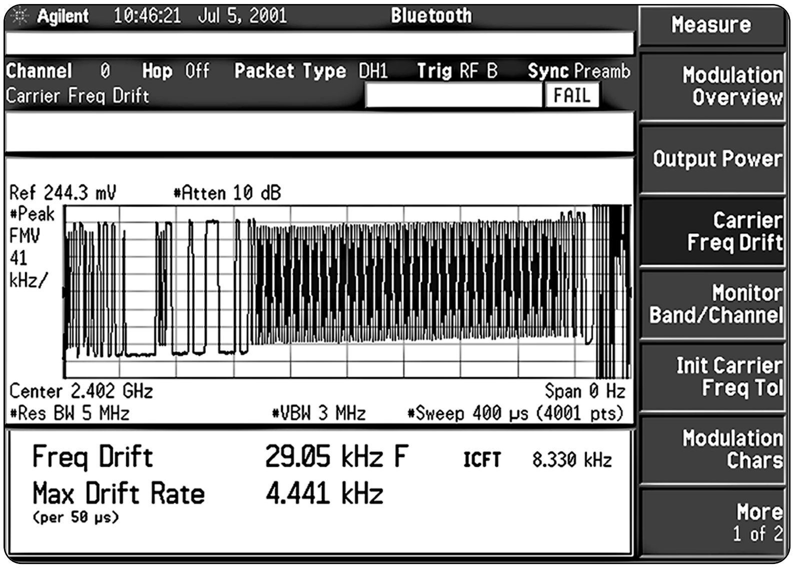


Figure 8: RF radio design using digital techniques.

B.2 Transmitter Attributes

Consider the question of how modulation is impressed upon the carrier. Shown in Figures 7 and 8 are one design with an IQ modulator and one with a phase-locked loop that unlocks during the burst to impress frequency deviations onto the carrier. The former is not susceptible to frequency drift while the latter is—it depends heavily on ‘unspecified’ parameters which can change from lot to lot or die to die, a largely unpredictable phenomenon. On the other hand, IQ modulation designs often require extensive calibration.



Channel 0 Hop Off Packet Type DH1 Trig RF B Sync Preamb
Carrier Freq Drift FAIL
#Atten 10 dB
Center 2.402 GHz Span 0 Hz
#Res BW 5 MHz #VBW 3 MHz #Sweep 400 μs (4001 pts)
Freq Drift 29.05 kHz F ICFT 8.330 kHz
Max Drift Rate 4.441 kHz
(per 50 μs)

Figure 9: Agilent ESA-E Spectrum Analyzer display of Frequency Drift.

Now consider the transmit power expected from the design. A number of questions occur: Is it a Class 1 design, which can transmit 100 times the RF power of Class 3? If so, is transmission through a separate RF stage? If that is so, exactly what is the vendor guaranteeing or measuring? You might need to reconsider the -20 dB spectrum test. If the end product is battery operated, it is important to control the power output via more precise output level adjustment. Does it need to be calibrated, or does the chip perform well enough without it?

B. 3
Transmitter Calibration

More questions arise over calibration. In cases where output level is dynamically adjusted because of RSSI feedback, does the design do this precisely, or must it be calibrated for every unit to ensure adequate transmit power step size? Calibration is a trade-off between time and performance—if calibration is done, greater accuracy and uniformity result, but it also takes more time. If the decision is to calibrate, you need to determine how it will take place—how many calibration points, how many iterations, how much time, etc.

Spectral content of the transmitter is of particular concern. An IQ modulation schema is usually more regulated than an FM/phase-locked loop design. This involves modulation characteristics and transmit bandwidth parameters (-20 dB spectrum test). Not shown in **Figure 9** are potential frequency conversion spurs that leak out of the transmitter. Where these occur and their relative levels depend on where they are generated and superimposed on the main signal, and whether they are amplified similarly to the desired signal. An examination of the transmitter's block diagram, provided by the IC vendor, will offer clues but, as in the case of RF design and test, there is no real substitute for actually measuring it.

APPENDIX C:
Characterization of the *Bluetooth* Radio

C.1
Transmitter (Modulation Characteristics Performance)

Generally, modulation characteristics should not change with level, but the same cannot be said about frequency. A modulation characterization vs. frequency test will likely yield one of two results. One, all frequencies will show a modulation index of about the same value, in which case only one frequency in the band need be tested. Second, the modulation index will increase or decrease over frequency. This brings up two related issues. First, the lowest index will reduce the link budget possible for the radio within a piconet, since a lower beta will decrease the signal-to-noise ratio—that is, reduce sensitivity. However, too high a beta will make the bandwidth too large, causing it to fail specification. After analyzing the situation, you may decide that the least desirable alternative is a low beta, in which case you would test at the frequency point where this would occur. A more conservative approach might be to test at a number of frequencies and compare the results with the IC manufacturer's data at, say, 20 dB bandwidth. The results could then be correlated to optimize testing at the IC level as well as the appliance (functional) level.

C.2
Transmitter (Power)

Output power is a very important parameter and may, as noted in the previous section, be calibrated. Whether it is or is not, certain frequency characteristics of the amplifier/filter/antenna path will almost certainly *not* be flat—unless very extensive calibrations are done,

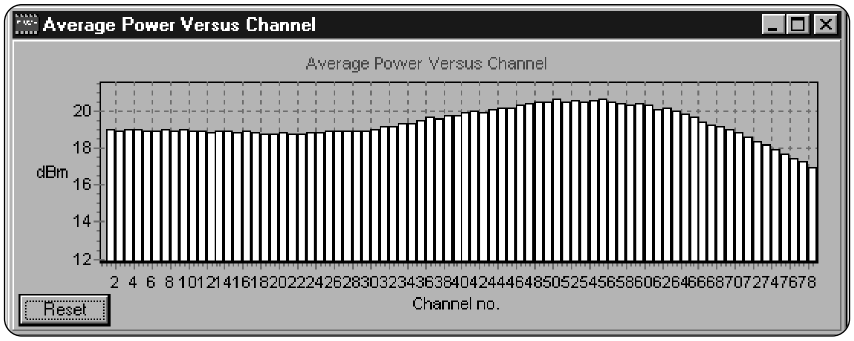


Figure 10: Trace display of power vs. channel.

which is usually unnecessary in *Bluetooth* manufacturing. Note the overall frequency response: Is it flat? Peaked in the center? Off center? Unpredictable?

In **Figure 10,** a trace display of power vs. channel (frequency) is shown. In this example, the response is peaked off center and dips at the highest frequency. If this is a standard characteristic and you want to ensure that the design does not dip below a certain level at any point, your focus should be at the high end of the band. Conversely, if the high and low frequencies randomly change in terms of lowest power, both of them should be measured. More importantly, you would then suspect that a parameter was varying within an IC, which could be very troublesome. Then you would want to measure not only the high and low frequencies, but also the middle, in order to account for the characteristic. Moreover, the ratio between the two (e.g., low- to mid-band) would be the verifiable number on which you would need to focus.

C.3
Receiver (Sensitivity)

Sensitivity is the most important receiver parameter in a *Bluetooth* enabled appliance. The SIG specification is .1% BER at <-70 dBm, which is measured by a regimen which changes different parameters of the transmitter signal. These extreme conditions will *not* normally be found in actual use, so the test can be simplified for manufacturing. In the case depicted in **Figure 11**, performance of the design was a signal-to-noise issue and the overriding influence was level.

The graph illustrates a measured sensitivity of approximately -84.5 dBm. Further study of the design revealed that impairments of timing error, frequency offset, and drift were not key contributors to BER when the signal was ~3 dB higher. Such information is not readily obtainable from the SIG tests, which are designed for certification; instead, the conditions must be swept independently and the design analyzed for its responses. In this case, even with a generous 3 dB degradation allowed for impairments, the performance was still 10 dB better than the SIG specification! That is a good selling point for this particular design, which allowed a high-margin sensitivity test that did not permit impairments. Furthermore, the test was very repeatable and dealt with the area of greatest concern—noise performance of the circuit (to which silicon, power supply, target appliance, and adjacent circuit noise were all contributors).

By considering such complex design characterizations—during both development *and* production—you will be able to create a more precise, streamlined, and efficient test plan for your product.

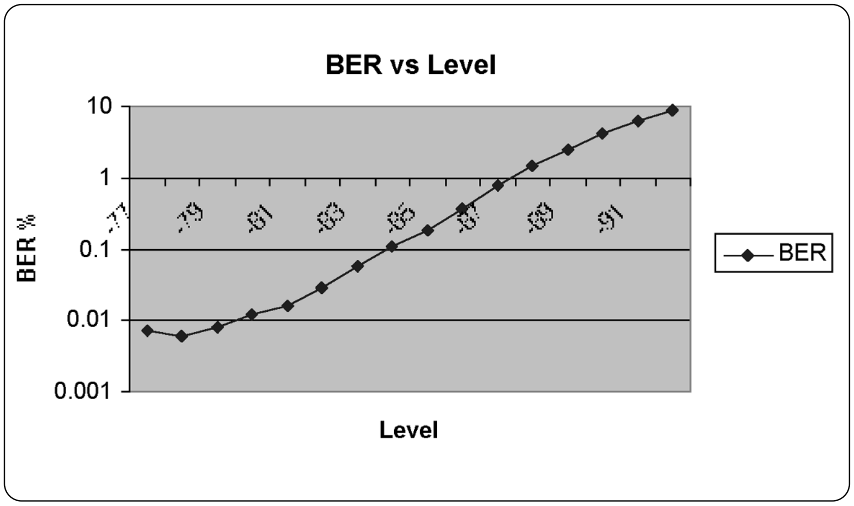


Figure 11: Sensitivity measurement showing bit error rate (BER) vs. level.

APPENDIX D:
Other Manufacturing Issues Detailed

D.1
Parallel Testing

Parallel testing and DUT interfacing (control and RF) largely determine test station architecture and design. For example, if you decide on true parallel testing, a duplicate set(s) of test equipment will be needed. DUT connection is never easy, and you will also have to ensure isolation between DUTs. This may be somewhat simplified since each DUT has direct connection to the test equipment.

If, on the other hand, you choose a sequential method that tests *n* DUTs at a time, the equipment will have to be switched to each DUT as it passes through the test area. This minimizes the equipment needed, but also complicates switching and calibration. A middle ground might be to evaluate how each component of the system is used, then duplicate only those components necessary to create a balanced, resource-sharing system appropriate for the desired throughput or volume. This would, of course, entail more complicated software planning and increase switching complexity over a direct connection.

D.2
DUT Interfacing and Fixturing

The DUT connection—specifically the RF connection—should be planned very carefully. Since *Bluetooth* is an RF technology and *Bluetooth* enabled products are generally built on high volume and low cost, testing must be done through a radiated or coupled connection, not a direct one. This presents a problem for adjacent units in the case of parallel testing, since they can be ‘jammed’ by RF interference from other DUTs if they are not adequately isolated. Hence test fixtures must provide the required isolation between units or erroneous data will result.

D.2.1
Performance of Fixtures

It is outside of the scope of this publication to discuss RF enclosure or fixture design in detail, but it is worth noting that many tests will depend crucially on the performance of fixtures (receiver sensitivity and transmitter power output, for example). Many companies, including Agilent, provide shielding on their RF test fixtures to guarantee isolation. Assuming that interface issues are addressed—isolation, control (RF leakage can take place here as well), switching, and so on—“performance” means that fixtures are calibrated for loss and that they maintain that loss characteristic over a long period of time. Calibration and loss characteristics are *major* determinants of test accuracy that must be addressed if testing is to be reliable.

Figure 12 illustrates the physical connection of a DUT to the test system and the mediating role of a fixture. Note that the fixture includes such items as power supplies and audio circuits; these have been included to show that fixture design can grow to be quite complicated.

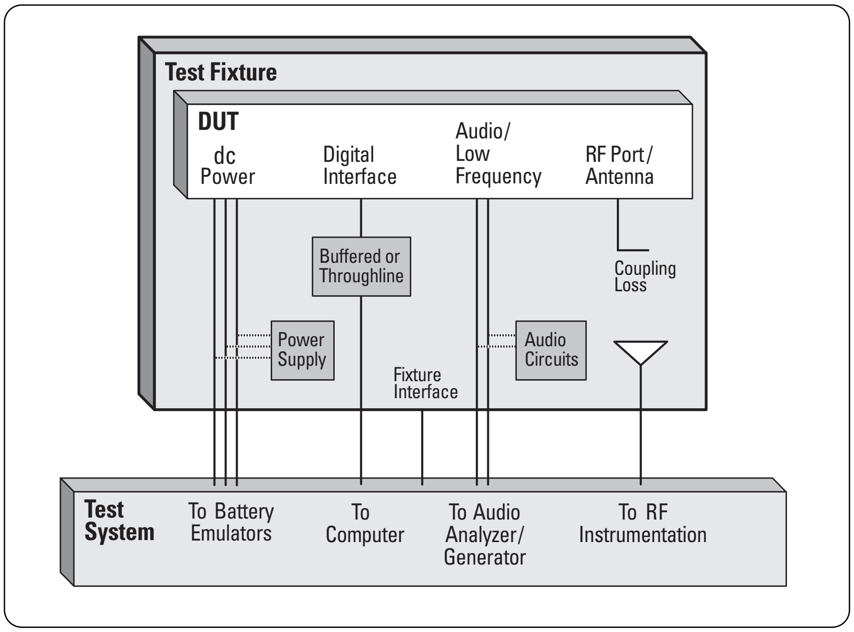


Figure 12: Diagram showing model of *Bluetooth* appliance DUT and connection to the test system through a fixture.

NOTE: **Connections from dc Power are to *either* battery emulators or power supply; likewise, connection from audio/low frequency are to *either* audio analyzer/generator or audio circuits. These alternatives are indicated by dotted lines.**

D.2.2
Calibration of Fixtures

To calibrate a fixture, we must first know its loss at the frequency at which it will be used. We have to measure this. However, when we do, we soon run into a host of measurement uncertainties—accuracy of the calibration signal, accuracy of power detector measurement, standing wave ratio (SWR) interaction, uncertainty between the calibration signal and the fixture, and uncertainty between the fixture and the power detector. Fixtures use a calculated term for loss, dB, which also has its own uncertainty, further affecting measurements on the DUT.

Uncertainties occur due to SWR between the DUT and the fixture, as well as between the fixture and the test station. Also, there is uncertainty of the loss value itself! If the detector at the test station is different from the detector used for calibration, more uncertainty will result. Because of these many sources you may want to investigate measurement uncertainty in the following documents:

- International Organization for Standardization (ISO), "Guide to the Expression of Uncertainty in Measurement," Second Edition, 1995
- Barry N. Taylor. and Chris E. Kuyatt, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," NIST Technical Note 1297, September 1994, U.S. Government Printing Office
- Sherry L. Read and Timothy R.C. Read, "Statistical Issues in Setting Product Specifications," *Hewlett-Packard Journal*, June 1988, pp. 6-11

D.2.3
Fixture Repeatability

Repeatability is a term used to quantify the degree of sameness in reading identical signals under identical conditions. It generally includes the amount of noise accompanying a signal from the environment. With a fixture, if a loss value (dB) changes over time, the test results will show a bias commensurate with the change. If it is pronounced, the change can overwhelm the effort to calibrate a fixture.

Hence it is a good idea to understand the factors which can cause change in loss value—and eliminate them. For example, station switches can change over time, so only high-repeatability switches should be used for RF testing. Second, RF connector interfaces can deteriorate with time, particularly if they are frequently changed out or altered. Good designs, therefore, will minimize the number of RF connectors used. The vibrational sensitivity of a fixture may also degrade the integrity of connections, including couplings from one antenna to another. Location may also play a role. In *Bluetooth* applications, near field couplings are generally used as opposed to far field couplings, but near field couplings are particularly sensitive to location—tenths of millimeters in offset may affect readings by many tenths of dBs.

D.3
Test Result Determination

Determining a test line limit (TTL), where a result from a test is compared against another number to trigger a PASS or FAIL, would seem to be an easy task, but in fact is rather complex. You should examine it from the outset of your test planning, since it will have a major effect on yields and may influence the equipment you select.

D.3.1
Yields

Bluetooth technology is used largely in low-cost, high-volume products, so manufacturing yields should remain high. What the exact number turns out to be will vary from product to product and company to company, but it should normally be above 95%. Since we are seeking to maximize profit, the natural goal is to make this number very high—if it is high enough, it can eliminate the need for a repair process.

Yields are a function of design margin, process integrity (assembly, handling, and test), and component value integrity. While many of these have been discussed earlier, one topic which needs further exploration is the determination of test line limits in the test process. **Figure 13** visualizes TLL.

D.3.2
The Specification Setting Model

The diagram shows a two-sided test spec. In many cases, a one-sided spec is appropriate—for example, in sensitivity measurements. The extra margin term is usually reduced to 0 to allow as wide a TLL as possible. The $n*\sigma$ numbers represent choices made by the manufacturer to produce the desired yield. An n of 2 to 6 is often chosen; an n of 2 will lead to a 95% yield, an n of 3 should result in 99% yield. Clearly, the larger the n, the closer the yield will come to 100%, since the distribution curve is a composite of variations in product, components, processes, etc. Outright failures are not considered part of this characteristic; however, they are certainly part of the ultimate yield! The goal is to find and eliminate the causes of failures and to 'push' the process to a tight normal distribution.

D.3.3
Establishing an Initial Distribution

The initial distribution should be determined by pilot run(s) and then refined over time as knowledge of the process increases. You should carefully monitor IC die and component lots, design changes, and other variables to ensure that older characteristics are not being incorporated into newer distributions.

D.3.4
Delta Environmental (ΔEnv)

A thorough analysis would take a large sample of units and measure the yield against changes in the environment (ΔEnv). A wide range of approaches could be taken. If the 'primary use case' is indoors, the range of temperature and humidity will normally be small; if outdoors (e.g., a cell phone), it will be larger. Also, the results will have both means and standard deviations. An aggressive approach might take only the means, while a conservative approach would include standard deviation (say, mean plus $2*\sigma$).

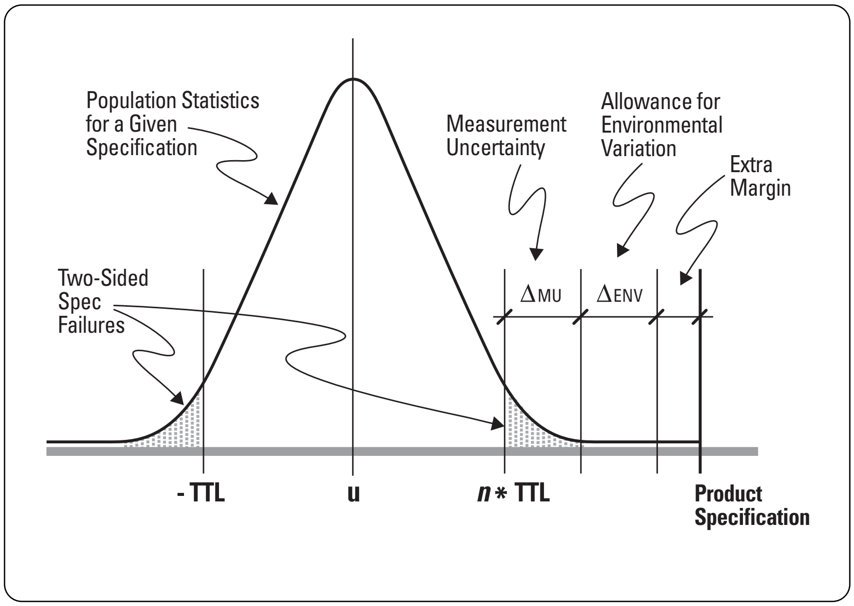


Figure 13: Specification (TLL) Setting Model

D.3.5
Measurement Uncertainty (ΔMU)

Measurement uncertainty (ΔMU) can be a significant factor in selecting a TLL. If the uncertainty is too large, it will drive the TLL to be tighter than necessary, causing more failures. You should choose equipment and methodologies for the yields and margins needed in your individual application. For example, if you are measuring power output, a product with an uncertainty of 1 dB may result in unsatisfactory margins compared to one that has .2 dB uncertainty (e.g., a precision power meter). A practical example of this is power setting—it is usually best to set the power as low as possible (within the specification) to avoid excess battery consumption. In this case, the power meter's precision would have to be worked into the system and tests to reflect this change.

APPENDIX E: Agilent Test Equipment for *Bluetooth* Technology

E.1
Test Equipment with *Bluetooth* Capability

1. **Bluetooth Test Set, E1852B**

   Establishes a link using standard *Bluetooth* protocol and verifies the performance of *Bluetooth* transceivers.

2. **Signal Generators, ESG-D Series (3-4GHz), Option UND, UN7, UN8**

   Bluetooth signal for transmitter tests, custom *Bluetooth* modulated interference signals for receiver testing, and *Bluetooth* receiver BER analysis.

3. **Spectrum Analyzer, ESA-A Series (3-26GHz), *Bluetooth* Bundles (Option 303, 304)**

   Automated "one button" test execution for *Bluetooth* transmitter measurements. Performs a broad range of spectrum measurements.

4. **EPM Power Meter and E9320 Power Sensors**

   Quick, easy, accurate *Bluetooth* transmitter power measurements.

5. **Simulation Software, ADS with *Bluetooth* Design Guide**

   Software tool for design and simulation of custom *Bluetooth* systems. Pre-defined *Bluetooth* component models help speed the simulation process. Can be linked with the ESG-D Series and 89600 Series.

E.2
Other Test Equipment

1. **Vector Signal Analyzers, 89400/89600 Series**

   Versatile and precise signal analysis with complete *Bluetooth* transmitter measurements. Modulation quality analysis for *Bluetooth* signals, including constellation and eye diagrams.

2. **DC Sources, 66319B/D**

   Fast, programmable dynamic DC power sources with battery emulation.

3. **Logic Analyzers, 16700 Series**

   Comprehensive system-level debugging for multiple processor/bus designs.

4. **Mixed Signal Oscilloscopes, 54620 Series**

   Verification and debugging of *Bluetooth* baseband signals.

5. **Network Analyzers, 8753E Series**

   Measurement of Antenna VSWR.

E.3
Accessories

1. **Oscilloscope Probe, 54006A**

   Passive probe with very low capacitance (0.25pF).

2. **Close Field Probe, 11940A**

   Magnetic field radiation up to 1GHz.

3. **Splitter, 11667A**

   Ratio measurements and equal power splitting.

4. **Directional Coupler, 773D**

   Monitors one RF waveform while two *Bluetooth* devices are connected by cables.

5. **Dual Directional Coupler, 772D**

   Monitors both RF waveforms while two *Bluetooth* devices are connected by cables.

APPENDIX F: References

The Official Bluetooth Website, **www.bluetooth.com,** includes information on *Bluetooth* history, technology, news, specifications, applications, products, events, and Special Interest Group (SIG).

1. *Specification of the Bluetooth System* – version 1.1, Volume 1 "Core," February 22, 2001, *Bluetooth* SIG

2. *Specification of the Bluetooth System* – version 1.1, Volume 2 "Profiles," February 22, 2001, *Bluetooth* SIG

3. *Bluetooth Test Specification* – RF A:2, 20.B.153/0.9, March 24, 200, *Bluetooth* SIG

4. *Bluetooth RF Measurement Fundamentals,* Agilent Application Note AN 1333-1 (lit. no. 5988-3760EN)

5. *Bluetooth RF Testing—The Right Test for the Radio Design,* Agilent article, May 2000

6. *Agilent Technologies' Bluetooth and Wireless LAN Test Products, Systems and Services,* Brochure (lit. no. 5988-4438EN)

7. *Investigating Bluetooth Modules,* Agilent Application Note AN 1333-2 (lit. no. 5988-2417EN)

8. *Considerations When Selecting a System Power Supply for Mobile Communications Device Testing,* Agilent Application Note AN 1310 (lit. no. 5968-2424E)

Note: References 4, 6, 7, and 8 are available on the Agilent *Bluetooth* website at **www.agilent.com/find/bluetooth.**

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