52nd ARFTG Conference Digest, pp. 128-139, Rohnert Park, CA, Dec. 3-4, 1998

NIST Passive Intermodulation Measurement Comparison for Wireless Base Station Equipment

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***Abstract* - The National Institute of Standards and Technology has initiated a passive intermodulation measurement comparison for the U.S. wireless industry. The goal is to determine the agreement in the measurements of third-order intermodulation products of passive devices made by participating companies for currently deployed communication bands. We provide the details of this comparison along with preliminary results. In addition, we present a model describing third-order intermodulation distortion within a cable assembly and show how the cable and load affect passive intermodulation measurements.**

INTRODUCTION

Passive intermodulation (PIM) is a form of signal distortion that occurs whenever signals at two or more frequencies conduct simultaneously in a passive device, such as a cable or connector, which contains some non-linear response. The non-linear behavior produces spurious signals whose frequencies are linear combinations of the frequencies of the original signals. Odd-ordered intermodulation (IM) products (e.g. $f(IM3)=2f_1-f_2$) are usually the most problematic in the wireless industry since they have the highest potential of falling within the receive band, or up-link, of a base station, creating rf interference in the receiver [1]. Although frequency allocations are specifically designed to guard against this problem, collocation of two or more base station transceivers at a single site substantially increases the risk of PIM interference [2], as illustrated in Figure 1.

Base stations built for mobile communications systems such as Personal Communication Service (PCS 1900), Advance Mobile Phone System (AMPS), Global System for Mobile communications (GSM), and Digital Communications System (DCS 1800), use DIN (Deutsche Industrinorm) 7-16 and Type N coaxial connectors to handle the high transmit power requirements. At high power (above 1 W), nonlinearities in coaxial connectors become apparent and measurable [3]. There are many possible causes of intermodulation in coaxial connectors and cables including poor mechanical contact, dissimilar metals in direct contact, ferrous content in the conductors, debris within the connector, poor surface finish, corrosion, vibration, and temperature variations. The sources of PIM have been studied extensively at various laboratories [4]-[8].

At the request of base station equipment manufacturers, the National Institute of Standards and Technology (NIST) has initiated a PIM measurement comparison for the U.S. wireless industry. The goal is to determine the agreement in PIM measurements made by participating companies for currently deployed communication bands. Two sets of artifacts were obtained for the comparison, one to be used as control standards by NIST, and the other to be circulated among the participants. Each set contains four two-port artifacts with DIN 7-16 connectors and varying levels of passive nonlinearity (on the order of -100 dBm for two 43 dBm signals). Here, we present preliminary results of the comparison. Due to the small number of data sets collected to date, we will show only the ranges at each of the data points without reporting average measured values in order to avoid biasing future results. Only after a significant number of participants have reported their data will we publish average values.

In addition to reporting the preliminary results of the comparison, we also present a model describing third-order IM distortion within a cable assembly using signal flow diagrams. This model allows us to show how the cable and load affect passive intermodulation measurements.

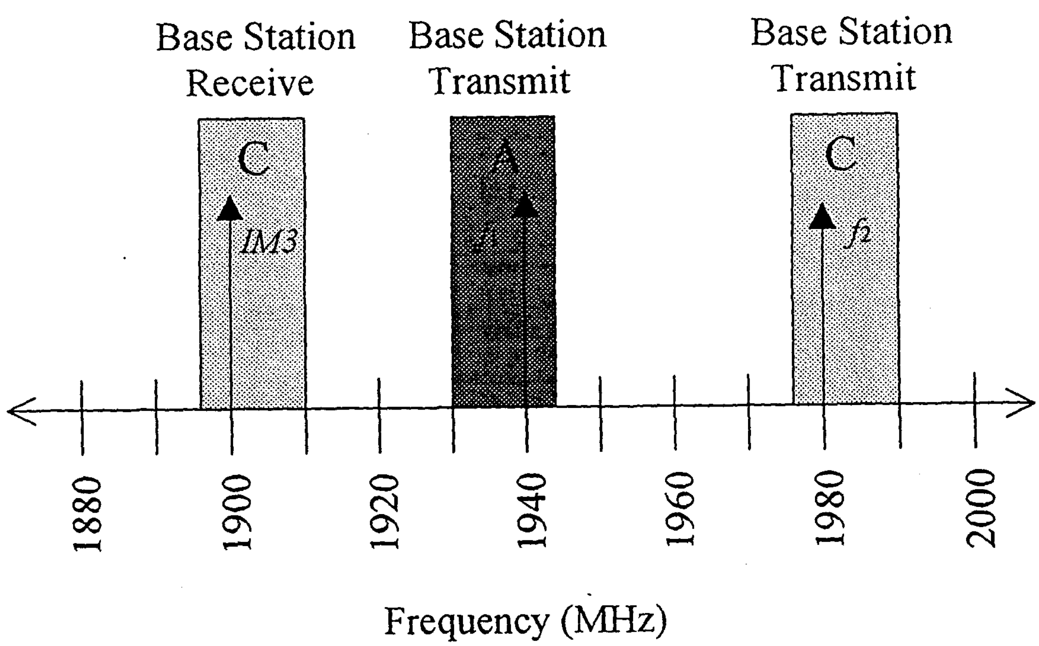

Figure 1. Potential third-order intermodulation distortion occurring in two collocated base station transceivers in the broadband PCS band. Bands A and C are both transmitting, and a nonlinearity causes a third-order IM distortion to appear in the receive area of band C. $f(IM3) = 2f_1 - f_2 = 2*1940 - 1980 = 1900$ MHz.

MOTIVATIONS

Before beginning the measurement comparison, we had the opportunity to collaborate with members of the RF Fields Group at NIST and a major telecommunications service provider in measuring passive intermodulation distortion of base station antennas. Service providers are now interested in measuring PIM of their incoming and field tested antennas. The new anechoic chamber at NIST allows such measurements with high isolation from external sources generating interference. In addition to measuring numerous antennas, we also looked at a number of other passive devices. One of the experiments performed was to compare two commercial cables used in PCS base stations. The powers of the third-order IM products of each cable were measured using two cw signal sources each measuring +40 dBm (10 W) at the instrument's test port, comparable to power levels they are exposed to in the field. Both cables had DIN 7-16 connectors and were supposedly within PIM specifications (*P* (*IM3*)<120 dBm). Figure 2 shows the results. While one cable clearly met specifications throughout the frequency range, the other one exceeded specifications at all frequencies by more than 30 dB. Thus, our corporate partner concluded that it was important to measure all passive components in a base station that have the potential of causing IM distortion, regardless of manufacturers' specifications.

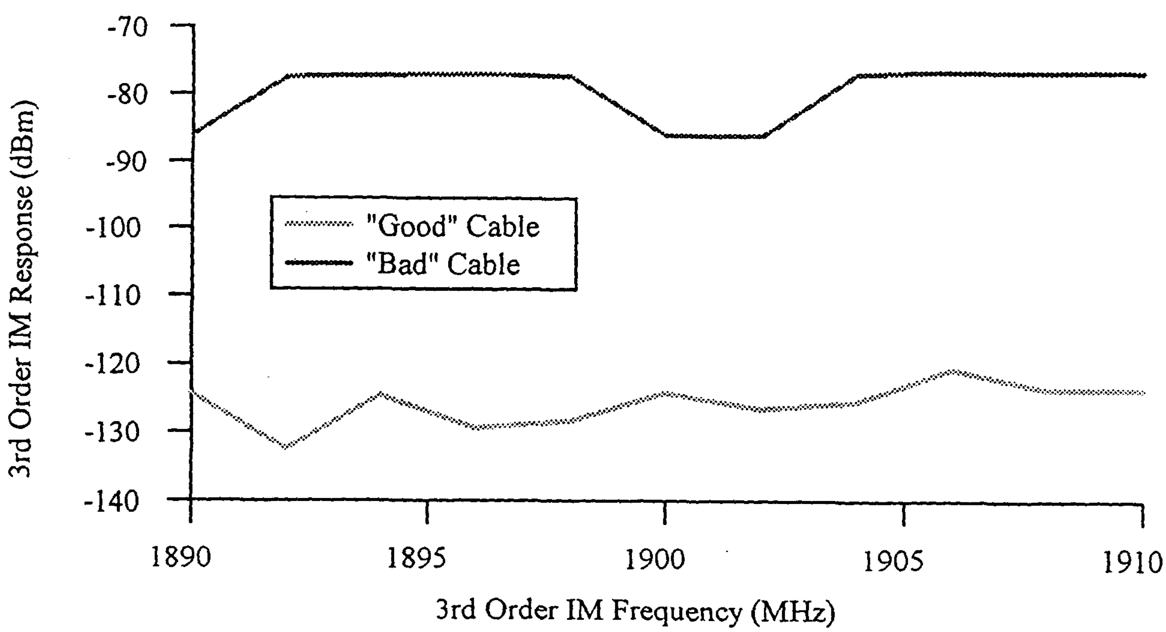

Figure 2. Third-order response of two commercial cables used in PCS base stations. The third-order IM products of each cable were measured using two cw signals each measuring +40 dBm. Both cables had DIN 7-16 connectors and were supposedly within manufacturers' specifications (*P*(*IM3*)<120 dBm).

Coaxial connectors can be a major source of intermodulation distortion in communications systems. Due to the high transmit power levels required at base stations, the two most widely used connector types are Type N and DIN 7-16. In the United States, the Type N connector has been widely used for many years, although the DIN 7-16 connector is rapidly becoming the connector of choice by base station equipment manufacturers. Previous publications [9] have reported that DIN 7-16 connectors show a measurable improvement in reducing PIM compared to the Type N connectors. We performed our own measurements on laboratory grade coaxial cables with Type N connectors using a commercial passive intermodulation analyzer to verify these claims. We applied two cw signal sources each measuring +40 dBm (10 W) at the instrument's test port, much like we did with the DIN 7-16 cables previously, only this time using an AMPS system. We found the third-order IM products to be in the range of -70 dBm at most frequencies, more than 10 dB higher than even the worst DIN 7-16 cable. Thus, we obtained our first evidence of the dramatic difference in PIM levels between the two types of connectors.

MEASUREMENT COMPARISON

The goal of the PIM measurement comparison is to determine the agreement in PIM measurements made by participating companies for currently deployed communication bands. For this comparison, two sets of artifacts were obtained, one to be used as control artifacts by NIST, and the other to be circulated among the participating companies. The artifacts are labeled with different colors to distinguish them: red, white, yellow, and blue. Each artifact has two ports with male and female DIN 7-16 connectors and varying passive nonlinearities.

For this comparison, the powers of the third-order IM products of each artifact are measured with two cw signal sources, each measuring +43 dBm (20 W) at the test ports, following the International Electrotechnical Commission's guidelines [10]-[11]. Each artifact is measured within the receive (up-link) band of any or all of the four communications bands, listed in Table 1, when the two +43 dBm signals are tuned to fall within the corresponding transmit (down-link) band. The minimum required data from each participant is a single third-order intermodulation power in one communication band.

Table 1. Receive and transmit frequencies for four communications bands.

Communication Band	Receive Frequencies (Up-Link)	Transmit Frequencies (Down-Link)
AMPS	824-849 MHz	869-894 MHz
PCS 1900	1850-1910 MHz	1930-1990 MHz
GSM	890-915 MHz	935-960 MHz
DCS 1800	1710-1785 MHz	1805-1880 MHz

Participating companies are asked to measure either or both transmitted (forward) or reflected (return) intermodulation products. To measure reflected intermodulation, participants are instructed to connect the male connector of the artifact to the active test port of their system and the female connector of the artifact to a low PIM load. To measure transmitted intermodulation, they are instructed to connect the male connector of the artifact to the active test port of their system and the female connector of the artifact to their own cable that is in turn connected to the receiving port of their system. Participants who have the ability to make swept frequency measurements are encouraged to make additional measurements at specified frequencies. Those who have systems that can measure intermodulation products in more than one communication band and those who have multiple systems are encouraged to measure the devices in as many different bands as possible.

The role of NIST in this comparison is to act as a pilot laboratory. Without knowing absolute PIM values, our tasks are to organize the comparison, keep a database of the measurements, and report the results. Our first responsibility was to procure a commercial passive IM analyzer and two sets of artifacts, one of which we keep in-house for measuring the long-term stability of our system, and the other of which we circulate among the participants. Currently, we are making measurements and sending the artifacts to each of the participating companies. After each company measures the set of four artifacts, they send them back to us, along with their data, and we remeasure the artifacts to ensure that they are still in working order, before sending them to the next company. At the end of this comparison, we will present each of the participants with a report showing how their measurements compared with everybody else's, keeping the other companies' identities confidential. Later, we will develop methods for determining absolute PIM values along with an uncertainty analysis, which is why we need a model.

Here, we present preliminary results of the comparison. Due to the small number of data sets collected to date, we show only variations in the data without reporting average measured values in order to avoid biasing future results. Only after a significant number of participants have reported their data will we publish average values.

Table 2 shows the measurement ranges for reflected PIM measurements taken at NIST of the control artifacts, where we define the range, in dB, as the difference between the highest measurement, in dBm, and the lowest measurement, in dBm, for a given device. The artifacts have so far been measured four times in a one month time span using a commercial AMPS-band PIM analyzer. Measurement ranges for each artifact are between 0.50 dB and 1.61 dB. These control artifacts will continue to be measured at regular intervals until the comparison is completed.

Table 3 shows the measurement ranges for reflected PIM measurements taken of the round-robin artifacts. The artifacts have so far been measured by the first three participants in the AMPS and GSM bands, but by only one participant in the PCS 1900 and DCS 1800 bands. The range for the red and white artifacts is surprisingly high (up to 8.32 dB), while the range for the yellow and blue artifacts ranges between 0.42 dB and 2.54 dB. The large initial ranges motivate us further in PIM measurement evaluation. After several more companies participate in the measurements, we will present the averages and standard deviations of the measurements on each artifact in all four bands.

Table 2. Measurement ranges are presented for reflected PIM measurements of the control artifacts. The artifacts have so far been measured four times in a one month time span using a commercial AMPS-band PIM analyzer.

Artifacts	Range (dB)
Red	0.50
White	1.61
Yellow	1.02
Blue	1.25

Table 3. Measurement ranges are presented for reflected PIM measurements of the round-robin artifacts. The artifacts have so far been measured by three participants in the AMPS and GSM bands, but only once in the PCS 1900 and DCS 1800 bands.

	Range (dB)			
Artifacts	**AMPS**	**PCS 1900**	**GSM**	**DCS 1800**
Red	5.91	-	1.97	-
White	8.32	-	5.18	-
Yellow	2.11	-	0.42	-
Blue	1.33	-	2.54	-

POINT SOURCE MODEL FOR REFLECTED THIRD-ORDER PIM

In addition to organizing the PIM measurement comparison, we have also developed a model that describes third-order IM distortion within a cable assembly. Although Deats and Hartman [8] have previously presented a model for exactly this purpose, we have developed an alternative model using signal flow diagrams, which allows us to simplify calculations for cables with loss or any other arbitrary two-port device, as well as taking into account reflections in the terminating load. Figure 3 illustrates this concept for reflected measurements, where the PIM analyzer detects intermodulation from the port to which the return power is delivered. Three signal flow graphs are required, one for each of the two frequency sources in the transmit (down-link) band, and one for the third-order IM frequency present in the receive (up-link) band. Here, we assume that PIM is generated only at the connectors of the cable, $IM3_1$ at Port 1 of the cable and $IM3_2$ at Port 2 of the cable. Figures 3a and 3b represent the two input frequencies, respectively, where nonlinearities in the connector pairs contribute to PIM generation. Figure 3c represents the third-order IM frequency, where the PIM is generated. The S-parameters of the cable and the reflection coefficients of the load are indexed to account for frequency variations.

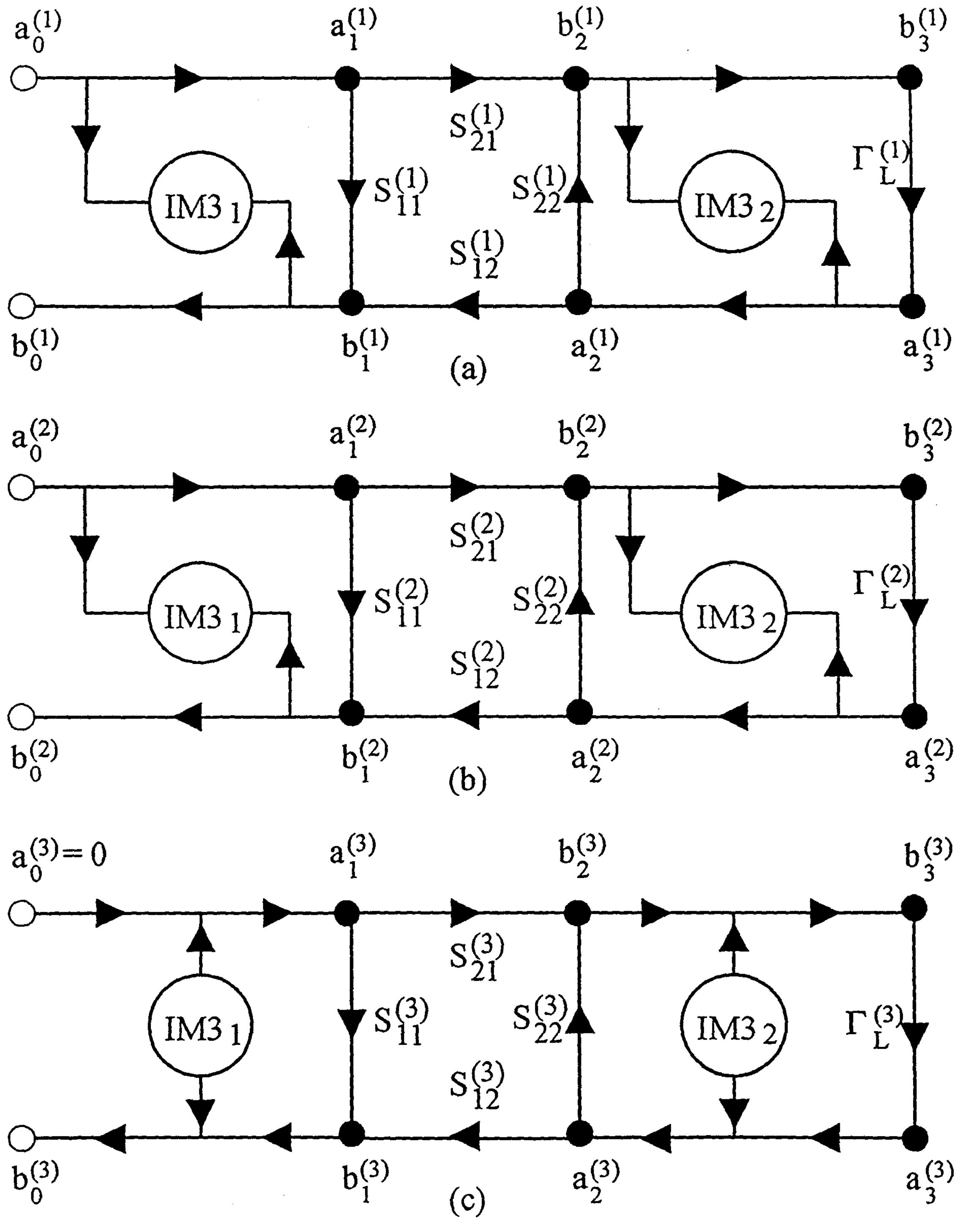

Figure 3. Point source model for reflected third-order PIM. (a) and (b) represent the two input frequencies where nonlinearities at each of the connectors contributes to third order PIM (c).

Solving for the output power $b_0^{(3)}$ using signal flow analysis, we obtain

$$b_0^{(3)} = (1 + S_{11}^{(3)})\ IM3_1 + \frac{S_{21}^{(3)}\ S_{12}^{(3)}\ \Gamma_L^{(3)}\ IM3_1 + S_{12}^{(3)}\ (1 + \Gamma_L^{(3)})\ IM3_2}{1 - S_{22}^{(3)}\ \Gamma_L^{(3)}} . \qquad (1)$$

The output power at the third-order IM frequency is a function of the two IM products, $IM3_1$ and $IM3_2$, as well as the S-parameters of the cable $S_{ij}^{(3)}$ and the reflection coefficient of the load $\Gamma_L^{(3)}$. Note that all of the terms in Equation (1) are complex quantities.

Equation (1) can be simplified if certain assumptions are made. For example, if the cable has zero length and no reflections, and the load is assumed to be ideal, then Equation (1) reduces to:

$$b_0^{(3)} = IM3_1 + IM3_2 . \qquad (2)$$

where the output power $b_0^{(3)}$ is simply the summation of the two IM products. If the cable is assumed to have zero length and no reflections, but there is reflection due to a mismatched load, then Equation (1) becomes

$$b_0^{(3)} = (1 + \Gamma_L^{(3)})\ IM3_1 + (1 + \Gamma_L^{(3)})\ IM3_2 . \qquad (3)$$

Finally, if the load is assumed to be ideal, but the cable has a nonzero length and reflections, then Equation (1) becomes:

$$b_0^{(3)} = (1 + S_{11}^{(3)})\ IM3_1 + S_{12}^{(3)}\ IM3_2 . \qquad (4)$$

To illustrate how this model and its simplifications predict IM performance, we make use of measured S-parameters of a typical cable and reflection coefficients of a low-PIM terminating load. For $IM3_1$ and $IM3_2$, we arbitrarily enter magnitudes of -100 dBm each. First we compare two of the simplified cases, Equation (2) where the cable has zero length and no reflections, and the load is ideal, and Equation (3) where the cable has zero length and no reflections, but the load is not ideal. Figure 4 plots the magnitude of $b_0^{(3)}$ versus frequency for both cases. As expected, for the case where both the cable has zero length and no reflections, and the load is ideal, $b_0^{(3)}$ is constant with frequency and is equal to the sum of two -100 dBm signals, or -97 dBm. When the cable has zero length and no reflections, but the load has some mismatch, $b_0^{(3)}$ varies with frequency and follows the same trend as the real part of the load's reflection coefficient, shown in Figure 5. In this case, the output power varies by 0.3 dB for a load reflection coefficient of approximately -25 dB.

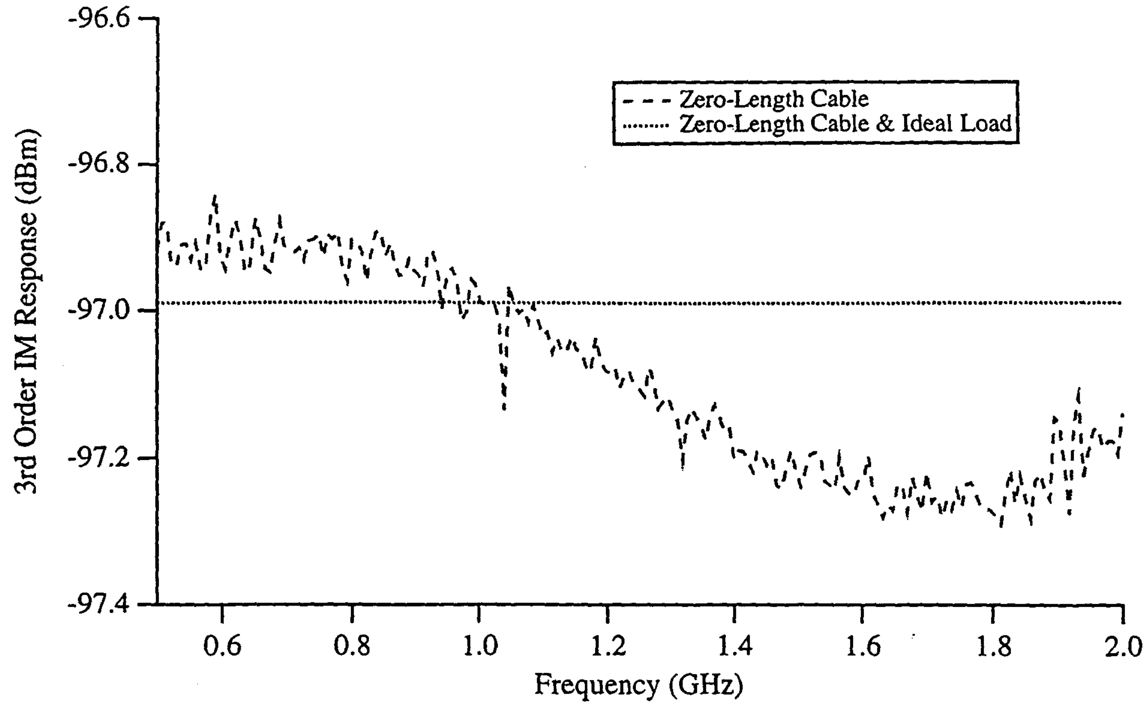

Figure 4. Modeled 3rd-order intermodulation response for two cases, one in which the cable has zero length and an ideal load, and one in which just the cable has zero length.

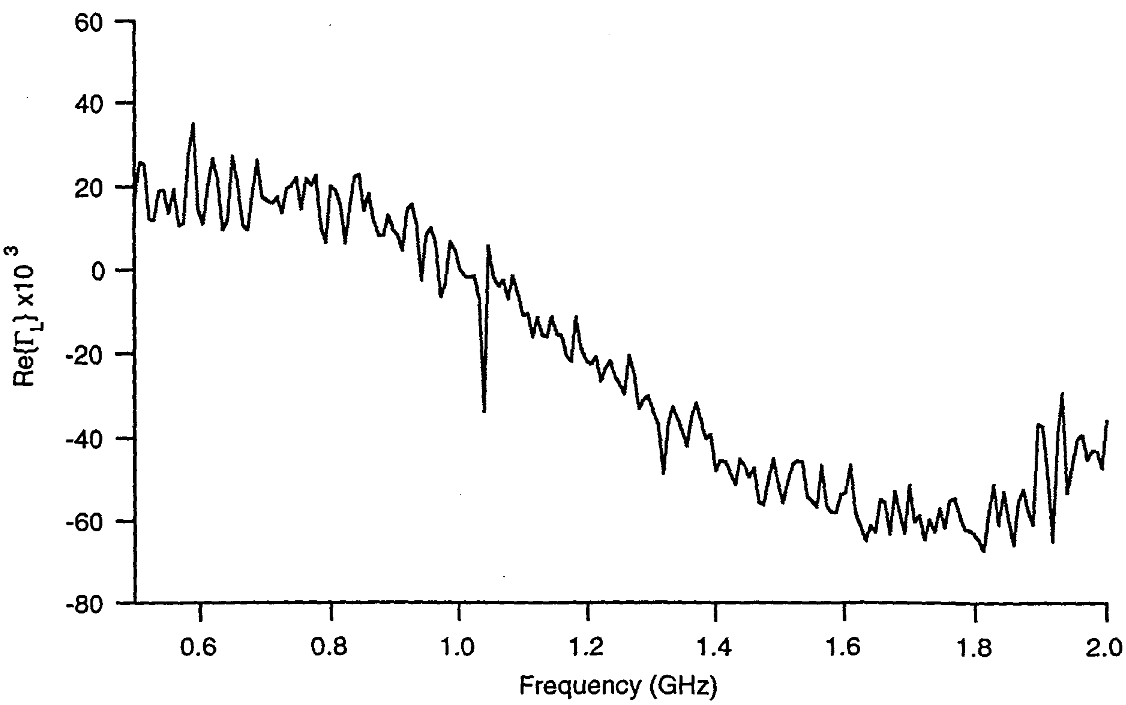

Figure 5. Real part of the measured reflection coefficient of a low-PIM load.

When we add Equation (1), which takes into account the full model, and Equation (4), which only assumes a perfect load, to the comparison, we get very different results. Figure 6 illustrates all four cases. When the cable has a nonzero length, the third-order IM response has several nulls where the two IM sources largely cancel each other out due to the phase constant of the cable. This is an important point because it shows that if PIM measurements are made only at a frequency where these nulls occur, it is possible to underestimate the value of PIM in the cable assembly. With a broadband measurement, a 15 dB discrepancy is measured. On the other hand, this fact can also be used to select a jumper-cable length in a base station that causes destructive interference resulting in lower IM.

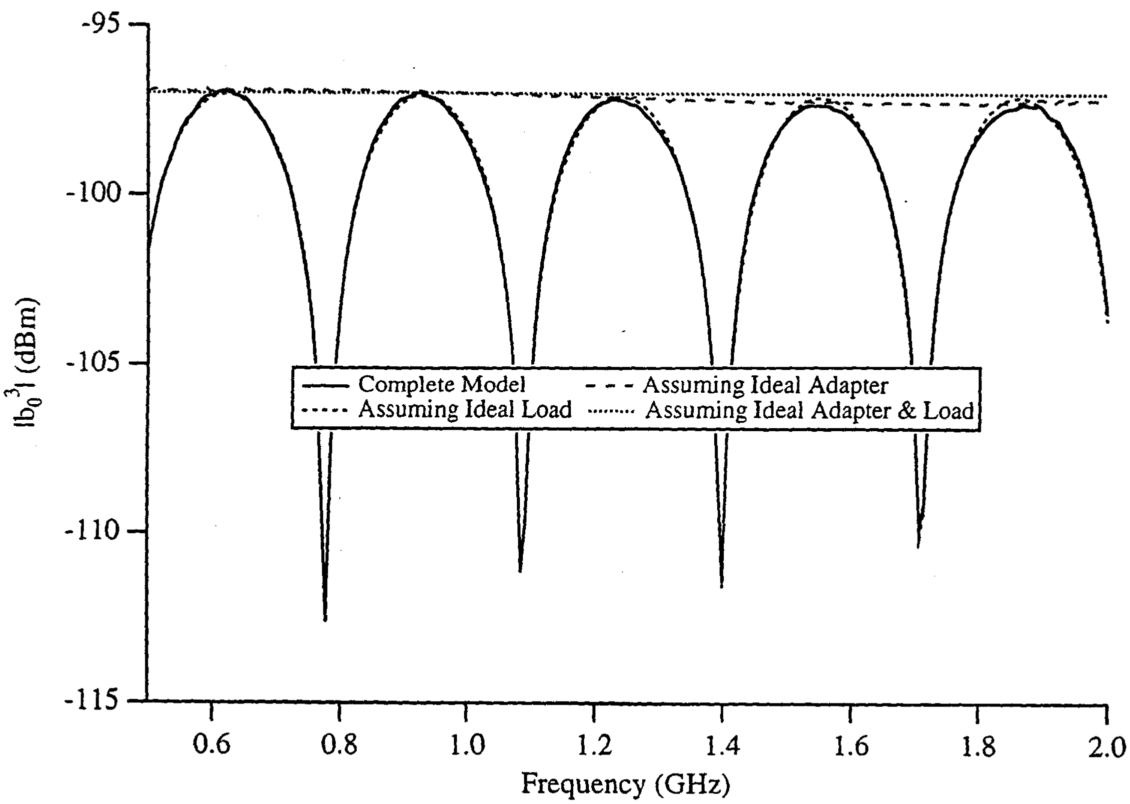

Figure 6. Calculated third-order intermodulation response for a reflected measurement using the point source model and three simplifying assumptions.

CONCLUSIONS

The passive intermodulation measurement comparison, currently underway, addresses a direct need expressed to NIST by U.S. base station equipment manufacturers. There is a critical need for accurate measurements of PIM in wireless communication base station components. Passive intermodulation has the potential of adversely affecting digital communications in cellular phones and personal communication systems, and the industry is currently limited in its ability to assess agreement in PIM specifications and measurements, particularly in regard to trade between the U.S. and the European Community. The PIM measurement comparison allows each participant to assess its capabilities in an impartial way, while it allows NIST to evaluate the urgency of any PIM measurement problems that may exist within the industry.

In addition to the comparison, we have developed a model which explains third-order IM distortion within a cable assembly. So far, we have shown how the cable and load can affect reflected PIM measurements. In the future, we plan to expand this model to take into account transmitted measurements, as well as the reflected measurements. We will also compare our model to actual measurements, with the goal of predicting PIM of a cable assembly with the knowledge of the connectors' PIM levels, the cable's *S*-parameters and the load's reflection coefficients. We think this model will lead to the development of a new deembedding technique for determining the PIM of base station antennas, which are usually measured at the end of a cable. Current measurements can only determine the PIM of the combined cable and antenna.

ACKNOWLEDGMENTS

The authors thank Robert Johnk, Dennis Camell, and Herbert Medley of the RF Fields Group at NIST, Chuck Gilbert of USWest Communications, Werner Wild of Spinner GmbH, and Rick Hartman, Brad Deats, and James Brunner of Summitek Instruments.

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