A Fast Procedure for Total Isotropic Sensitivity Measurements of Cellular IoT Devices in Reverberation Chambers

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Abstract—We present a method that allows a fast evaluation of total isotropic sensitivity (TIS) with the use of continuous-mode stirring in a reverberation chamber (RC). A limited number of standard stepped-mode measurements are taken to calibrate the continuous-mode measurements by computing the offset between the measured sensitivity level of the device and the device-reported reference signal received power (RSRP). A comparison of the results from the method proposed here and the standard stepped-mode approach illustrates that the measurement results of the fast approach can be within 0.2–0.5 dB of the standard method and allows for a test time reduction of up to 90%.

Index Terms—Cellular device, Internet of Things (IoT), measurement uncertainty, over-the-air (OTA) test, reverberation chamber (RC), total isotropic sensitivity (TIS), wireless system.

I. INTRODUCTION

C ELLULAR wireless devices have become ubiquitous over the past decades. In the 1990s, while voice communication with mobile phones was the most common application of cellular technology, more recent data-oriented applications, such as cellular hot spots (i.e., wireless local area networks), Internet of Things (IoT), machine-to-machine (M2M), and industrial IoT (IIoT) applications, seemed likely to dominate future cellular wireless applications. In 2015, IoT technology was reported to have a potential global economic impact of US \$4 trillion to US \$11 trillion annually by 2025 [1]. Estimates indicate that the number of connected wireless IoT devices will increase from 10.3 billion in 2020 to 20.5 billion in 2030 [2]. Ensuring the over-the-air (OTA) performance of

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mobile phones and IoT devices is, therefore, a critical task, and very frequently, a time-consuming one.

A critical metric for verifying the OTA performance of cellular technology is the lowest received power level that still allows a reliable connection, called "total isotropic sensitivity" (TIS) [3] or "total receiver sensitivity" (TRS) [4]. It is evaluated using a target error rate, such as bit error rate (BER), block error rate (BLER), or data throughput in response to a controlled reduction in base-station output power [3].

The iterative procedure utilized in the standardized "Normal" TIS tests (note that "Normal" and "Fast" will be capitalized in this work to clearly differentiate between the specific TIS test methods) consists of a decrease in the base station emulator's (BSE) transmitted power level in small steps until the specified target error rate threshold is found to be within predefined limits. The power level at which the error threshold is exceeded is termed the sensitivity level. TIS is an integrated quantity.

In order to calculate TIS using reverberation chambers (RCs), the device sensitivity is sampled over many steppedmode-stirring (or tuning) states [5], [6], [7], [8], [9], 10], [11], [12] and the formula to calculate TIS can be derived the same way as for anechoic chambers (ACs) [7]. The application of RCs to evaluate TIS was introduced almost 30 years ago, and today the use of RCs for both total radiated power (TRP) and TIS measurements is widely adopted [13]. The Normal TIS approach using RCs is, therefore, well established and has been used for many years [3]; agreement between RC and AC methods for OTA testing of singleinput, single-output (SISO) IoT devices has also already been established [11].

Normal TIS measurements, whether performed in ACs or RCs, require considerable time because measurements are made at low power levels where noise can be an issue, and time-consuming reconnections may be required. TIS test times can be especially long for category M1 (CAT-M1) and narrow-band (NB)-IoT protocols due to their low data rates and the correspondingly long sample-acquisition time. To reduce TIS test time, it is advantageous to perform measurements at higher power levels. The high signal-to-noise ratio (SNR) helps to minimize the time versus accuracy tradeoff because fewer samples must be averaged to reliably estimate the device's

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sensitivity and because there are fewer dropped calls during the measurement. Another source of time reduction is the use of device-reported received-power sensitivity levels, as opposed to inferring the sensitivity from an error-rate measurement. It is worth emphasizing that RCs have several advantages over ACs, such as lower cost and the possibility of placing the device under test (DUT) in any subset of the working volume [15].

A Fast TIS method for ACs was proposed in 2016 [8], [9]; a comparison of the results and the power-stepping Normal TIS approach showed acceptable agreement and test time reduction for Global System for Mobile Communication (GSM) and Wideband Code Division Multiple Access (WCDMA) protocols¹. For RCs, however, to the best of the authors' knowledge, a Fast TIS method has yet to be reported in the literature. The method presented in this article takes advantage of faster continuous-mode measurements (in comparison to steppedmode ones) and the use of device-reported received power levels to expedite the determination of the TIS. In addition, continuous stirring maximizes the number of field configurations the DUT is exposed to during the tests [16], [17], not restricting the experiment to a predefined finite set of stirring mechanisms' configurations. Another key feature is that the measurement samples are collected at high received-power levels, resulting in a high SNR for much of the data.

The remainder of this article is presented as follows. In Section II, the proposed RC-based method is derived. In Section III, results from five different frequency bands and two different devices, a cellular handset and an NB IoT device, are presented. In Section IV, uncertainties are computed for each of the five bands. The results demonstrate the applicability of the method, with a reduction of the test time to less than 8% of the standard time, but still with good agreement with the Normal RC-based TIS method and with expanded uncertainties that meet or nearly meet current Cellular Telecommunications and Industry Association (CTIA) test requirements, exceeding the threshold by at most 0.2 dB. Section IV presents the main conclusions and discusses future work.

II. DESCRIPTION OF THE FAST TIS METHOD

A. Background: Normal TIS in RCs

The proposed Fast TIS method aims at producing results within a specified level of uncertainty in as little time as possible for SISO IoT devices. A schematic representation for both Normal and Fast TIS measurements in RCs is shown in Fig. 1.

In Normal TIS measurements, the search for the lowest BSE output power associated with a predefined performance metric (e.g., BER) threshold value starts with a relatively high BSE power. At a fixed, stepped-mode-stirring state n, the power is decreased until the eighbourhood of the error threshold value is reached. This indicates that the measurement is approaching the sensitivity threshold of the DUT for that stepped-mode-stirring sample, termed $P_{\text{DUT,sensitivity},n}$.

Reverberation chamber



Fig. 1. Setup for TIS measurements of a wireless DUT. For Normal TIS, the power incident on the device is near the sensitivity level of the device. For Fast TIS, the initial BSE power is set to be sufficiently high to obtain a relatively noise-free value of RSRP at location j.

The BSE power is then increased or decreased, in smaller steps, in order to better estimate $P_{\text{DUT},\text{sensitivity},n}$ for that sample [3]. Note that we use the term $P_{\text{DUT},\text{sensitivity},n}$ rather than $P_{\text{TIS},n}$ to distinguish a single sensitivity sample from the total sensitivity.

The power received by an antenna depends on factors such as antenna pattern, polarization, and angle of arrival of the incident wave. It can be demonstrated that the received power of a device antenna can be calculated by integrating the average power that would be received by an ideal isotropic antenna [18]. In an AC, the TIS can be computed from the sum of the inverses of polarized effective isotropic sensitivities [19]. In RCs, TIS is computed from a series of measurements that are harmonically averaged; that is, P_{TIS} is calculated from a collection of $P_{\text{DUT},\text{sensitivity},n}$ values [3]. Consequently, in order to estimate the TIS of the device, the harmonic average of the *N* stepped mode-stirring samples is calculated. In addition, in RC measurements, chamber loss, cable loss, and reference-/measurement-antenna effects also have to be accounted for. This can be written in linear units as [3]

$$P_{\text{TIS}} = G_{\text{ref}} e_{\text{meas}} \eta_{\text{meas}} G_{\text{cable}} \left(\frac{1}{N} \sum_{n=1}^{N} \frac{1}{P_{\text{BSE},n}} \right)^{-1}.$$
 (1)

Note that while (1) is in units of Watts, P_{TIS} is typically reported in dBm or dBm/15 kHz. In (1), e_{meas} is the antenna mismatch factor, η_{meas} the radiation efficiency, and G_{cable} cable loss in the cable assembly that connects the BSE to the measurement antenna, and G_{ref} is the reference power transfer function.

The magnitude of G_{ref} corresponds to the loss in the chamber for a given configuration. This value of G_{ref} is used in the calculation of both TRP and TIS values to relate power at the BSE to power at the DUT as determined through a reference measurement [3], [12]. Note that, while TIS is a device sensitivity-related measurement, TRP is a measure of the total power radiated by a device measured in all directions. RCs have been used to test devices for both TRP and TIS, allowing, it is worth emphasizing, the calculation of uncertainties [5]. G_{ref} can be calculated in

¹"Acceptable agreement" is here defined as agreement between the Fast TIS method and the Normal TIS method to within their expanded uncertainties with negligible residual bias [13].

linear units as [3], [11]

$$G_{\rm ref} = \frac{\frac{1}{\rm NF} \sum_{n=1}^{N} \sum_{f=1}^{F} |S_{21}(f,n)|^2}{e_{\rm meas} \eta_{\rm meas} e_{\rm ref} \eta_{\rm ref}}$$
(2)

where frequency averaging is conducted over *F* frequencies across the channel of interest and stepped mode stirring is carried out over *N* stepped-mode-stirring states, e_{ref} is the mismatch of the reference antenna, and η_{ref} is the radiation efficiency of the reference antenna. Generally, G_{ref} is measured over several independent realizations of the stirring sequence, and the standard deviation represents the uncertainty due to the lack of spatial uniformity [20]. In the present work, we used 12 independent realizations to estimate G_{ref} . The same value of G_{ref} is used for stepped- and continuous-mode measurements, and G_{ref} is typically reported as a negative gain in decibels (dB, negative dB values).

Note that the harmonic average is used in (1) in order to align with the CTIA test plan for AC measurements [3] where a lower weight is given to samples in the nulls of the DUT's antenna pattern. In the RC, the harmonic mean is used to reflect the dependence between samples $G_{\text{Ref},n}$ and $P_{\text{BSE},n}$ in estimating the intrinsic sensitivity of the DUT (that is, for a sample collected at a high chamber loss $G_{\text{Ref},n}$, a high value of $P_{\text{BSE},n}$ is required, and vice versa). As for the AC method, Horansky et al. [21] indicated that harmonic averaging might reduce the uncertainty in the estimate of TIS as compared to either normal averaging or the median.

As stated above, the drawbacks of the RC-based Normal TIS method include the following.

- The measurements in the Normal TIS approach are taken in the neighborhood of the sensitivity threshold values. This leads to a time-consuming adjustment of the BSE power in the vicinity of the target value and to the greater likelihood of call drops.
- 2) The measurements are taken in stepped mode, with the paddles or any other stirring mechanisms in fixed positions. This requires that the stirring mechanism moves to a new position and stops and stabilizes (wait for mechanical oscillations to stop) for the measurements to be performed.
- 3) As well, the $P_{\text{DUT},\text{sensitivity},n}$ for each mode-stirring state is inferred from the measurement of an error metric such as BER, and in the Fast TIS method, the device-reported received power is the primarily measured quantity, corrected to reflect the sensitivity level with an offset.

B. Continuous-Mode Measurements

The method proposed here aims at overcoming the drawbacks of the Normal TIS method by performing the measurements for TIS calculation at higher BSE power levels while the paddles move continuously. In the method, an offset between the Normal TIS values and the device-reported "reference signal received power" (RSRP) is defined, and for this, a limited number of stepped-mode sensitivity-level measurements is still required.

The procedure is comprised of two main parts. First, a continuous-mode measurement of the DUT is performed to

form the distribution of received power samples measured in the RC. Second, a series of stepped-mode offset calibration samples are acquired to shift these values to reflect the receiver sensitivity.

Because the stepped-mode offset calibration is a critical yet time-consuming part of the procedure, a separate section is devoted below to a study of the number of samples to be used. As illustrated in Section III, in general, a larger number of continuous-mode samples may be required for lower frequency bands to achieve a given accuracy level due to the reduced number of modes that the chamber will support at lower frequencies. The exact number of samples required for a desired level of accuracy depends on the size of the chamber and the level of correlation between the pseudorandom measurement samples.

In the first part of the Fast TIS procedure, continuousmode measurements are taken. The device-reported RSRP is recorded at many continuous mode-stirring states using a relatively high transmit power level from the BSE, $P_{\text{BSE,start}}$, to provide ideally error-free received samples quickly and with good SNR. These samples are denoted as $P_{\text{DUT},j}$ in Fig. 1. The goal of this measurement is to capture the distribution of samples provided by the RC under continuous stirring so that an appropriate average value can be computed and subsequently calibrated.

The number of continuous-mode-stirring samples that should be collected will depend on the level of accuracy required. This number may differ from the number of stepped-mode samples required for Normal TIS. We study this with a convergence metric based on the standard uncertainty for various thresholds in Section III.

For the measurements reported here, a total of J = 165 continuous-mode samples were used. The continuous movement of the paddles and turntable was intentionally made slow in order to minimize dynamic effects. Results showed the convergence to the Fast TIS value to be sufficiently unbiased. After approximately 100 samples, the standard uncertainty in the collection of samples dropped below our desired threshold (+/-1.0 dB), as discussed in Section III. We used J = 165, as discussed in Section III (Measurement Results and Discussion) below.

Fig. 2 compares the distribution of sensitivity levels of Normal TIS [see Fig. 2(a) and (c)] and Fast TIS [see Fig. 2(b) and (d)] measurements in LTE Band 7 (2655 MHz) and LTE Band 17 (740 MHz). Results for Fast TIS are calibrated, as described in Section II-C. In the plots, the final TIS values for each case are indicated by the solid red vertical line. As can be seen, the TIS values agree well, although the distributions differ. These differences will be the subject of future research.

C. Calibration of the Continuous-Mode Data With a Stepped-Mode Offset

As mentioned above, a calibration step is required to relate the continuous-mode data to the DUT's sensitivity level. This calibration is illustrated graphically in Fig. 3. A setup, such as the one schematically represented in Fig. 1, is used.



Fig. 2. Distribution of sensitivity levels at multiple mode-stirring states collected for: (a) and (c) Normal RC-based TIS using relatively low BSE output power; and (b) and (d) Fast TIS using relatively high BSE output power and device-reported received power values. Normally averaged (arithmetic mean) values are represented by a vertical dashed line. The harmonically averaged values calculated using power in Watts indicated by a vertical red line, correspond to the TIS. Results are shown for LTE Band 7 (2655 MHz) and LTE Band 17 (740 MHz).

At a stepped mode-stirring state *m*, the RSRP of the DUT, RSRP_{stepped,m} is recorded for a relatively high BSE output power, termed $P_{\text{BSE,start}}$ (see Fig. 3, step 1). Then, at the same physical location, the sensitivity level $P_{\text{DUT,sensitivity,m}}$ of the DUT for the specified error-rate threshold is measured and recorded by the BSE as for a Normal TIS measurement (see Fig. 3, step 2).

The goal of the offset calibration is to relate the DUT-reported RSRP_{stepped,m} to the BSE-measured value of $P_{\text{DUT,sensitivity,m}}$ for a limited number of M stepped mode-stirring states. Theoretically, the offset between the two metrics RSRP_{stepped,m} and $P_{\text{DUT,sensitivity,m}}$ should be identical for each stepped mode-stirring state; however, in practice, it is necessary to compute the offset from multiple stepped mode-stirring states due to nonidealities in the test setup, the DUT, and the fixed reporting step sizes for both RSRP_{stepped,m} and



Fig. 3. "Offset_{UE,m,stepped}" found at location m relates the RSRP value obtained with a BSE power level of PBSE_{,start} (RSRP_m) to the power at the device sensitivity threshold, which is found in the normal way with a stepped reduction of P_{BSE} .

 $P_{\text{DUT,sensitivity},m}$. These elements are quantified in Section IV on the uncertainty analysis.

Thus, the process to calculate $P_{\text{DUT,sensitivity},m}$ values using (1) is repeated at several uncorrelated positions (different stepped-mode-stirring states). At each position, *m*, an offset value is calculated by relating, in decibels, the sensitivity level to the high-power RSRP

$$offset_{UE, stepped, m} = RSRP_{stepped, m} + P_{DUT, sensitivity, m}.$$
 (3)

Here, $P_{\text{DUT,sensitivity,m}}$, where m = 1, ..., 10, is obtained for the *m*th stepped mode-stirring sample. In (3), $P_{\text{DUT,sensitivity,m}}$ and RSRP_{stepped,m} are reported in dBm. Note that RSRP may first need to be converted from the -17 to 97 RSRP reported value scale to power in dBm [22].

The median of the M offset values obtained in the various uncorrelated stepped-mode-stirring channel states corresponds to a calibration coefficient offset_{UE} that relates RSRP to receiver sensitivity (see Fig. 3).

The Fast TIS method utilizes a limited number of M stepped-mode measurements for the offset calibration samples, which are time-consuming since a search for the DUT's sensitivity level must be conducted for each of the m samples. These are combined with the continuous-mode-stirring measurements, which are faster, requiring no power search and no intermittent movement. The tradeoff between measurement time and accuracy for obtaining the M offset calibration samples will depend on the user's application. In Section II-E, we provide data on some specific aspects of the proposed method, including the impact of the number of stepped-mode calibration samples on the Fast TIS result and the number of continuous-mode samples required.

D. Calculation of Fast TIS

Once the offset has been determined, it is possible to estimate the sensitivity of the device by applying the offset to the J continuous-mode RSRP samples. For the jth sample, we have

$$P_{\text{DUT, sensitivity, fast, }i} = \text{offset}_{\text{UE}} - \text{RSRP}_{i}.$$
 (4)

In the present work, J = 165 with j = 1, ..., J, offset_{UE} is in decibels and $P_{\text{DUT,sensitivity,fast}, j}$ and RSRP_j are in dBm. The Fast TIS is then calculated using the harmonic average of the $P_{\text{DUT,sensitivity,fast}, j}$ values in Watts [3] as

$$P_{\text{TIS, fast}} = \left(\frac{1}{J} \sum_{j=1}^{J} \frac{1}{P_{\text{DUT, sensitivity, fast, }j}}\right)^{-1}.$$
 (5)

The final value is reported in dBm.

E. Number of Offset Calibration Samples

During the calculation of Fast TIS, sensitivity-level samples are calculated by subtracting the reported RSRP of the DUT from the offset defined in the stepped-mode calibration as in (4). Because of the significant measurement time required to obtain each stepped-mode sample of $P_{\text{DUT},\text{sensitivity},m}$, it is desirable to minimize the value of M from which the offset is estimated.

The minimum number of calibration samples depends on the chamber configuration, equipment being tested, stirring sequence, frequency, and several other factors. For the measurement setup used here, a value of M = 10 offset calibration samples allows an estimate of Fast TIS that varies by less than 0.5 dB over six independent sets of 165 continuousmode samples and for five different frequency bands and two different DUTs, as will be shown in Section III. As well as, past experience shows that M = 10 provides a similar level of variation for Fast TIS in other measurement setups and chambers. A CTIA round robin test is underway to further study the number of offset calibration samples required in practice. The uncertainty related to the offset calibration samples is discussed in Section IV.

III. MEASUREMENT RESULTS AND DISCUSSION

The proposed Fast TIS method was utilized for five cases with two different devices (a cell phone and an NB-IoT device) using different radio-access technologies (LTE, GSM, and NB-IoT) and at different frequencies. These cases are shown in ascending order of frequency in Table I. The channel center frequencies, channel numbers, error-rate thresholds, and the coherence bandwidth of the measurement setup for each case are shown in Table I. Fig. 4 is a photograph of the chamber setup for the test of the NB-IoT device.

The general approach for all cases started with the continuous-mode measurements, and then the stepped-mode offset measurements were performed. The median of the k = 10 offset measurements (3) was taken, and the offset was determined.

For the measurements reported here, a total of 990 samples were recorded with continuous movement of mechanical paddles and turntable, yielding RSRP values, which were used to calculate the sensitivity values $P_{\text{DUT,sensivity,fast}, j}$. The resulting power sensitivity values were randomly reordered to minimize correlation and grouped into six subsets with 165 samples

TABLE I Experiment: Five Different Bands Were Studied

#	Band	Freq. (MHz)	Ch.	Chan. BW (MHz)	TIS BER threshold	Coh. BW (MHz)
1	LTE B17 downlink	740	5790	10	5.00%	6.75
2	NB IoT B28	790	9435	0.18	5.00%	4.92
3	GSM B5	882	190	0.20	2.44%	5.54
4	NB IoT B1	2140	300	0.18	5.00%	2.58
5	LTE B7 downlink	2655	3100	10	5.00%	3.47

Fig. 4. Photograph of the chamber setup with an NB-IoT device. The reference antenna on the left and NB-IoT device on the right side of the turntable undergo a similar stirring sequence. The measurement antenna (not shown in the figure) is on the right-hand side of the photograph.

each. Although randomization does not remove all correlations between samples, results showed the convergence of the Fast TIS value to be sufficiently unbiased when compared to the Normal TIS values.

To evaluate the time versus accuracy tradeoff of the proposed Fast TIS method, results from the five cases were compared to Normal TIS results calculated using 200 stepped mode-stirring samples. For the Fast TIS estimate, we used a convergence metric based on the standard uncertainty s_J in the number of continuous-mode samples. The Fast TIS method was evaluated by the time required for $P_{\text{TIS,fast}}$ from (5) to converge to $s_J = 1.0, 0.5$, and 0.2 dB for an increasing number of Fast TIS sensitivity samples.

The standard uncertainty was computed as the standard deviation of the mean of $P_{\text{TIS,fast}}$ (corresponding to the Type A standard uncertainty, see [14] "Evaluation of measurement data") (s_J) for various numbers of J continuous-mode samples. Note that this metric was used to study the time versus

TABLE II Comparison of Results From Normal TIS and Fast TIS, Where Fast TIS Was Computed as the Average of the 165 Samples for Each Subset in Fig. 5(A)–(e)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
#	Band	Normal	Time	Fast	Abs.	Mean	Max.	CM ^a	Calibr.	FAST	Mean	Max.	Fraction
		TIS	(min)	TIS	error	error	error	time	time	TIS	time	time	of time
		(dBm)	()	(dBm)	(dB)	(dB)	(dB)	(min)	(min)	(min)	(min)	(min)	(%)
1	LTE	-91.35	72.52	-90.77	0.58	0.73	1.16	4.92	2.00	6.92	6.93	6.93	9.55
	B17			-90.79	0.56			4.93		6.93			
				-90.36	0.99			4.92		6.92			
				-90.19	1.16			4.93		6.93			
				-90.78	0.57			4.93		6.93			
				-90.80	0.55			4.93		6.93			
2	NB	-91.45	339.83	-92.27	0.82	0.67	0.96	11.00	11.00	22.00	22.01	22.02	6.48
	IoT			-92.38	0.93			11.02		22.02			
	B28			-91.89	0.44			11.02		22.02			
				-92.18	0.73			11.00		22.00			
				-92.41	0.96			11.02		22.02			
				-91.66	0.20			11.00		22.00			
3	GSM	-102.81	91.10	-102.41	0.40	0.24	0.53	4.17	3.00	7.17	7.17	7.17	7.87
	B5			-103.34	0.53			4.17		7.17			
				-103.06	0.25			4.17		7.17			
				-102.93	0.12			4.17		7.17			
				-102.84	0.03			4.17		7.17			
				-102.91	0.10			4.17		7.17			
4	NB	-95.29	357.48	-94.98	0.30	0.56	0.83	11.00	11.00	22.00	22.01	22.02	6.16
	IoT			-96.00	0.72			11.00		22.00			
	B1			-96.11	0.83			11.00		22.00			
				-94.86	0.42			11.02		22.02			
				-94.83	0.45			11.00		22.00			
				-95.92	0.64			11.02		22.02			
5	LTE	-95.84	49.47	-96.09	0.25	0.25	0.31	4.37	3.00	7.37	7.38	7.38	14.92
	B 7			-96.01	0.17			4.38		7.38			
				-96.06	0.22			4.37		7.37			
				-96.09	0.25			4.37		7.37			
				-96.15	0.31			4.38		7.38			
				-96.11	0.27			4.38		7.38			

^aContinuous-mode.

accuracy tradeoff by comparing the Fast TIS estimate to the Normal TIS estimate and does not represent the final measurement uncertainty in the Fast TIS estimate. The standard uncertainty can be given by

$$s_J = \frac{\sigma_J}{\sqrt{J}} \tag{6}$$

where J is the number of continuous-mode samples (Remley et al. [15] analyzed procedures to evaluate the correlation between samples, which is required to use (6)) that were used to calculate the standard deviation σ_J of the J continuous-mode sensitivity values. The metric from (6) was calculated for an increasing number of J samples. When the value of s_J dropped below a desired threshold, the time was recorded.

Note that the common formulation for standard deviation for quantities estimated from the harmonic mean holds only when the samples differ by relatively small amounts (less than a few dB) due to the nonlinearity introduced by averaging an inverse quantity. This condition may not always hold and is the subject of current research; however, in this work, continuous-mode sensitivity values (in linear values) were used to calculate the standard deviation and the standard uncertainty in order to evaluate convergence.

Convergence curves for Cases 1–5 are shown in Fig. 5(a)–(e), and corresponding values for J = 165 samples and M = 10 offset samples are given in column 5 of Table II.

While Fig. 5 illustrates the concepts, Table II provides some additional details for completeness. For each graph, the six blue curves represent the Fast TIS value calculated using an increasing number of samples J in (6) for each of the six subsets. The *x*-axis represents the time to collect these samples. The vertical lines in Fig. 5(a)–(e) represent the time required to obtain the standard uncertainty (s_J) from (6) equal to 1.0 (\Box), 0.5 (×), and 0.2 dB (Δ) For example, for all six subsets in Fig. 5(a), a value of $s_J = 1.0$ dB was reached in less than 0.4 min, a value of $s_J = 0.5$ dB in between 0.4 and 1.0 min, and a value of $s_J = 0.2$ dB in between 3.2 and 4.6 min.

Continuing with the example of Fig. 5(a), most of the six subsets of 165 values converged to a value close to -90.8 dBm (Table II, column 5) as the number of samples increased. The stepped-mode Normal TIS result was -91.35 dBm, illustrated by the thick red line in Fig. 5(a) and given in column 3 of Table II. The thinner horizontal red lines correspond to ± 1.0 dB around the Normal TIS value. Fig. 5(a)–(e) show little bias in the results, with the Fast TIS results sometimes above and sometimes below the Normal TIS values.

In Cases 2–4, shown in Fig. 5(b)–(d), the value of our convergence metric $s_J = 0.2$ dB was not reached in the time range considered. Thus, we see only two sets of vertical lines for these NB protocols (NB-IoT B28, GSM B5, NB IoT B1). This illustrates an expected increase in uncertainty for NB technologies because frequency averaging can significantly



Fig. 5. Fast TIS results from Cases 1–5 (LTE B17, NB IoT B28, GSM B5, NB IoT B1, and LTE B7). Blue curves represent the average Fast TIS with increasing number of samples. The vertical lines represent the standard uncertainties (s_J) equal to 1.0 (\Box), 0.5 (×), and 0.2 dB (Δ) In Cases 2, 3, and 4, the standard uncertainties $s_J = 0.2$ dB were not reached in the time range considered. The horizontal red lines indicate Normal TIS (thick line) and ± 1.0 dB limits (thinner lines). (a) LTE B17 Fast TIS average, $\pm s_J$. (b) NB IoT B28 Fast TIS average, $\pm s_J$. (c) GSM B5 Fast TIS average, $\pm s_J$. (d) NB IoT B1 Fast TIS average, $\pm s_J$. (e) LTE B7 Fast TIS average, $\pm s_J$.

reduce uncertainty in RC measurements of wireless devices [25].

The standard uncertainty values are related to the expected reproducibility of the results for various time thresholds (reproducibility will generally be better with a longer time threshold). We include this component in the uncertainty analysis of Section IV for 165 samples, which is the number given in the proposed standardized test methodology of [24]. This represents one of three additional components of uncertainty related to Fast TIS.

Table II provides additional information that compares Normal and Fast TIS. For example, the difference between

COMPARISON OF RESULTS FROM NORMAL TIS AND FAST TIS, WHERE FOR EACH BAND THE FAST TIS IS THE AVERAGE OF THE SIX SUBSETS AT THE 1-DB STANDARD UNCERTAINTY THRESHOLD SHOWN BY THE SQUARES IN FIG. 5(A)–(E)

TABLE III

1	2	3	4	5	6	7
#	Band	Mean error (dB)	Max. error (dB)	Mean time (min)	Max. time (min)	Fraction of time mean (%)
1	LTE B17	0.97	2.53	2.18	2.37	3.26
2	NB IoT B28	0.71	1.28	12.92	14.42	4.24
3	GSM B5	0.53	1.14	3.45	3.58	3.93
4	NB IoT B1	0.73	1.05	13.20	13.82	3.87
5	LTE B7	0.62	0.99	3.19	3.67	7.41

the mean of the six Fast TIS estimates and the Normal TIS estimate was less than 0.75 dB and the maximum difference was 1.16 dB for all five cases analyzed in this work considering all 165 samples collected in continuous mode (Table II, columns 7 and 8, "Mean error" and "Maximum error," respectively).

Further, the time required for the Normal TIS tests is considerably higher than for the Fast TIS. For example, for B17, the lowest frequency band that we studied, the time required for Normal TIS (column 4 in Table II) in Case 1 is 72.52 min, whereas the time required for Fast TIS (comprised of the calibration time and continuous-mode sampling, columns 9 and 10) is, on average, 6.93 min (columns 11 and 12): 9.55% of the Normal TIS time (column 14). The fraction of time required for the highest frequency band that we studied in Case 5 (LTE band B7) was 14.92%. For Cases 2, 3, and 4, the time is even shorter. These results demonstrate one of the main advantages of the Fast TIS method, the great reduction in the required measurement time.

Whereas Table II focused on results when all 165 continuous mode samples were used, Table III illustrates the results obtained considering a 1.0 dB standard uncertainty threshold (6), which is of interest to the CTIA as they consider relaxing the uncertainties for certain types of IoT device measurements. Recall that the 1.0 dB threshold value is represented by a square (\Box) in the plots in Fig. 5.

As shown in column 3 (see Table III), the mean error for the 1.0 dB standard uncertainty threshold is 0.97 dB for LTE B17 (Case 1). In the same column, the mean errors for the other cases are somewhat smaller. The mean errors of the five cases in column 3 of Table III are comparable to the results obtained when the full sequences with 165 samples of the Fast TIS tests are taken into account (Table II, column 7).

The reduction in time is, however, far more pronounced. The Fast TIS mean and maximum time in Table III, columns 5 and 6, respectively, correspond to the Fast TIS values

TABLE IV UNCERTAINTY BUDGET FOR LTE, NB-IOT, AND GSM. EXPANDED WITH A 2.0 COVERAGE FACTOR

Uncertainty contribution	Std. unc. (dB)
Contributions: DUT measurement part	
Mismatch: BSE – measurement antenna	0.06
BSE absolute output level (stability)	0.60
Cable factor – measurement antenna	< 0.01
Insertion loss – measurement antenna cable	< 0.01
Stability search step size	0.15
Temperature variation (calculated using 1 K)	0.14
Miscellaneous uncertainty	0.10
1 – Chamber lack of spatial uniformity (LTE B17)	0.40
2 – Chamber lack of spatial uniform. (NB-IoT B28)	0.40
3 – Chamber lack of spatial uniformity (GSM B5)	0.60
4 – Chamber lack of spatial uniformity (NB-IoT B1)	0.50
5 – Chamber lack of spatial uniformity (LTE B7)	0.25
Frequency resolution for TIS measurement	0.05
1 – Limited number of CM ^a samples (LTE B17)	0.19
2 – Limited number of CM ^a samples (NB-IoT B28)	0.45
3 - Limited number of CM ^a samples (GSM B5)	0.33
4 - Limited number of CM ^a samples (NB-IoT B1)	0.47
5 - Limited number of CM ^a samples (LTE B7)	0.08
Offset calibration sensitivity measurement	0.64
RSRP step size	0.14
1 - LTE B17	1.04
2 - NB-IoT B28	1.11
3 - GSM B5	1.16
4 - NB-IoT B1	1.16
5 - LTE B7	0.97
Contributions in the reference measurement part	
Mismatch: VNA – reference antenna	0.05
Mismatch: VNA – measurement antenna	0.06
VNA absolute level and level stability	0.06
Insertion loss: calibrated reference antenna cable	< 0.01
Insertion loss: measurement antenna cable	< 0.01
1 – Chamber lack of spatial uniformity (LTE B17)	0.12
2 – Chamber lack of spatial uniform. (NB-IoT B28)	0.12
3 – Chamber lack of spatial uniformity (GSM B5)	0.17
4 – Chamber lack of spatial uniformity (NB-IoT B1)	0.14
5 – Chamber lack of spatial uniformity (LTE B7)	0.07
Antenna: radiated efficiency reference antenna	0.27
1 - LTE B17	0.31
2 - NB-IoT B28	0.31
3 - GSM B5	0.34
4 - NB-IoT B1	0.32
5 - LTE B7	0.30
Total expanded uncertainty	Expanded with
	cover. factor
1 – LTE B17	2.16
2 – NB-IoT B28	2.31
3 – GSM B5	2.42
4 – NB-IoT B1	2.41
5 – LTE B7	2.04

^a165 Continuous-mode samples were used.

again calculated as the sum of the calibration time and the continuous-mode sampling for this case. As shown in column 7 (see Table III), the fraction of time needed for Fast TIS as compared to Normal TIS for the 1.0 dB standard uncertainty threshold are 3.26% (LTE B17), 4.24% (NB-IoT B28), 3.93% (GSM B5), 3.87% (NB-IoT B1), and 7.41% (LTE B7). Again, it is important to consider that a complete uncertainty analysis would be needed to estimate the final accuracy of the Fast TIS method in this case.

IV. UNCERTAINTY ANALYSIS

An estimate of the uncertainty in the measurements is presented in Table IV. The contribution of each part, DUT measurement, and reference measurement were calculated separately using root-sum-of-squares and then added using the root-sum-squares [3], [23]. Three additional components of uncertainty introduced by the use of the Fast TIS method are included in the DUT measurement section (the reference measurement remains the same as for the Normal TIS). The first is the standard uncertainty corresponding to the limited number of continuous-mode samples, computed with (6) for 165 samples as specified in the proposed CTIA Fast TIS method and discussed in Section III. There are two new terms related to offset calibration. One corresponds to the limited resolution of the RSRP steps (1 dB increments), and the other encompasses components corresponding to DUT measurements. These are described in more detail below at the end of the DUT measurement contributions.

Referring to Table IV, we start with the DUT measurement contributions. The mismatch between the BSE and the measurement antenna was calculated from [23, Sec. G.1] using the reflection coefficients of the antenna cables. The BSE absolute output level was provided in the specifications of the equipment used. The cable factor of the measurement antenna and insertion loss of the antenna cable were both negligible [23, Sec. G.2]. The stability search was specified in [23, Sec. G.11]. The uncertainty contribution due to temperature variation was calculated considering an ambient temperature uncertainty of ± 1 K [23, Sec. G.9] and the miscellaneous uncertainty magnitude of 0.1 dB is a fixed value [23, Sec. G.13].

Values of the uncertainty contributions due to RC's lack of spatial uniformity for Cases 1–5 were calculated from the variation between independent realizations of the stepped mode-stirring sequence (σ_{Gref}) for each band [15]. The contribution in the DUT measurement uncertainty due to frequency resolution for TIS measurements was determined from [3, Appendix 3].

The last three uncertainty contributions in the DUT measurement part correspond to the use of the proposed Fast TIS method [24]. The standard uncertainty due to the limited number of continuous-mode samples was computed from (6) based on a total of J = 165 samples used in the experiments. These values are different for each band, as shown in Table IV. As described in the next two paragraphs, for the offset calibration, the uncertainty consists of two parts, one related to the RSRP_{stepped,m} values and the other related to the estimation of the $P_{\text{DUT,sensitivity,m}}$ values.

For the former, because of the limited resolution of the reported RSRP values (which uses 1 dB steps), we assume that the "true" value of received power can occur uniformly anywhere within a -1/2 dB to +1/2 dB range. To estimate the effect of this on the uncertainty in the Fast TIS approach, in a simulation study, we calculated the mean and the median of uniformly distributed samples randomly selected over this interval. The simulation was based on a uniform distribution generated for an increasing number of samples *s*, the mean and median for each sequence with *s* elements were calculated





Fig. 6. Standard deviation of the mean and median for a simulation of various numbers of offset calibration samples taken randomly from a uniform distribution. Two million realizations were used in the simulation.

and the standard deviation of the mean and median results was computed. We repeated this calculation two million times and computed the standard deviations, obtaining a standard deviation of the median values of 0.138 dB, which we rounded off to 0.14 dB. This value is included in our uncertainty analysis as "RSRP step size." Note that the uncertainty based on the median will be somewhat higher than the uncertainty based on the mean, as shown in Fig. 6, where a similar simulation study was carried out for the mean of the samples, as well as for the number of offset calibration samples (s) ranging from 1 to 100.

For the estimate of the uncertainty in the $P_{\text{DUT,sensitivity,m}}$ values, because these samples are collected using the normal sensitivity search with the BSE (described in Section II-A), we consider the components of uncertainty related to DUT measurements, with the exception of the chamber lack of uniformity since the channel is fixed. As shown in Fig. 5(c) and (d), Fast TIS results converge from both below and above to the Normal TIS convergence curve, indicating that there is no significant systematic uncertainty in the approach. Here, we refer to Table IV and include the limited step size of the BSE threshold search (0.15 dB), the temperature variation (0.14 dB), and the BSE absolute output power level stability (0.6 dB). Combining these terms in radio subsystem [received signal strength (RSS)] (in decibels) results in a value of 0.64 dB.

Referring to the reference measurement part of Table IV, the impedance mismatch between the VNA and reference antenna, and the VNA and measurement antenna, were again calculated from [23, Sec. G.1]. The uncertainty contribution of the VNA absolute level and level of stability was provided in the equipment specifications. The uncertainty contribution of the calibrated reference antenna cable insertion loss was negligible [22, Sec. G.2]. The reference antenna cable insertion loss contribution was negligible as well [25]. Uncertainty contributions due to the lack of spatial uniformity of the reference measurements for each band were again computed from the variation between independent realizations of the mode-stirring sequence, but because the mean reference value is determined from the twelve measurements (not to be confused with the six DUT measurements that we used to determine the reproducibility of the measurement), this value is $(12)^{1/2}$ smaller than for the (single) DUT measurement. The last item, the uncertainty in the radiated efficiency of the reference antenna, was calculated from [12].

The total expanded uncertainty for the five frequency bands used in the tests is presented at the end of Table IV. In the calculation, a 2.0 coverage factor was applied, as specified in [3], and then the results were converted to decibels. Case 5 (LTE B7) has the lowest total expanded uncertainty (2.04 dB), whereas the highest total expanded uncertainty (2.42 dB) occurred in case 3: GSM B5. Cases 1 and 5 presented total expanded uncertainties that lay below the maximum 2.3 dB limit for TIS [23], while the others exceeded this limit by less than 0.2 dB. CTIA is currently adopting less-stringent uncertainty limits for IoT devices to support the use of Fast TIS methods.

V. CONCLUSION

We introduced an RC-based Fast TIS method that allows the estimation of the intrinsic TIS for a cellular-enabled wireless device. The method is based on continuous-mode samples collected in a RC that is calibrated with a limited set of stepped-mode samples. Experiments with cellular handsets and IoT devices utilizing LTE, GSM, and NB-IoT radio technologies showed that the method yields results that are comparable to the Normal TIS approach in only a fraction of time: in the worst case (NB-IoT devices), less than 15% of the time required by the Normal TIS method.

We also analyzed the uncertainty of the measurements and demonstrated that, for these devices and this set of measurements, the total expanded uncertainty using the proposed approach is either within or does not significantly exceed the CTIA limits for TIS measurements.

There are several refinements that should be studied for future work, including the effect of the stirrers' speed in the continuous-mode measurements, which also affects the distribution of the continuous-mode samples. Also, the calculation of the standard deviation when samples are harmonically averaged should be investigated further.

The study presented here illustrates the tradeoff between the uncertainty in the Fast TIS results and efficiency in terms of the time required to conduct the tests. Results indicate that this may be a promising method to evaluate many types of cellular devices, including low-cost NB-IoT, LTE, and GSM devices where reduction of measurement time is of the utmost importance.

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