I&M framing Topics

Instrumentation and Measurement in Communication Systems

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The demand for ubiquitous connectivity is challenging the physical constraints placed upon current communication systems. In addition, customers expect higher and higher quality from their service providers. Consequently, equipment manufacturers are required to produce systems that can be quickly deployed and provide bandwidth-efficient communications. To meet this goal, instrumentation and measurements play a fundamental and invaluable role.

At early stages of equipment development, rigorous testing is performed to both assess system functionality and performance and ensure system interoperability. Moreover, the increasingly complex nature of communication signals is placing additional pressure on design teams, already faced with tight project deadlines. Not only must the developer perform conformance testing; he/she must also quickly infer from measurement results root causes of possible technical problems.

The strategic importance of measurements in the field of communication systems is corroborated by the significant increase in the number of papers on this topic - both submitted and accepted - experienced by *IEEE Transactions on Instrumentation and Measurement* (TIM) in recent years. Unfortunately, many submitted papers are rejected because they fall clearly outside the journal scope. This fact motivated us – as researchers in the field—to write this paper to specify what can be considered an instrumentation and measurement (I&M) technical contribution in the field of communication systems.

Communication System Basics

With regard to the technical literature, a communication system is a facility consisting of physical plants, different types of equipment (transmitters, receivers, repeaters) and various accessories or enhancements (encryption, security solutions, and interoperability/networking), aimed at disseminating information according to the user needs. All of the individual elements must serve a common purpose, be technically compatible, employ common procedures, respond to some form of control and generally operate in agreement [1]. For the sake of clarity, a simplified general architecture of a typical communication system is sketched in Fig. 1.

Three major elements have to be highlighted: sender (or data source), channel, and receiver (or data sink). The sender is committed to communicate some sort of information, normally in digital form (i.e., a digital bit stream). The channel is used to convey the information from the sender to the receiver. It refers either to a physical transmission medium such as a wire, or to a logical connection over a multiplexed medium such as a radio channel, and has a certain capacity, often measured by its bandwidth in Hertz or its data rate in bits per second. The receiver is in charge of capturing the information and converting it to a usable form.

To really highlight the role of measurement, it is helpful to refer to a typical and widespread wireless communication system operating at radio frequency (RF). Its detailed architecture is depicted in Fig. 2. Additional readings are in [2], [3] and other references.

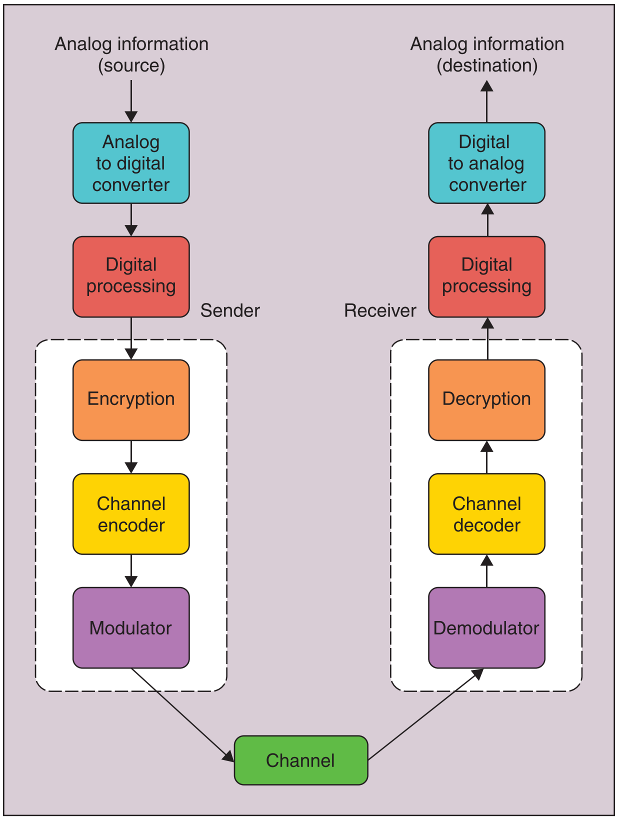

Fig. 1. Simplified general architecture of a typical communication system.

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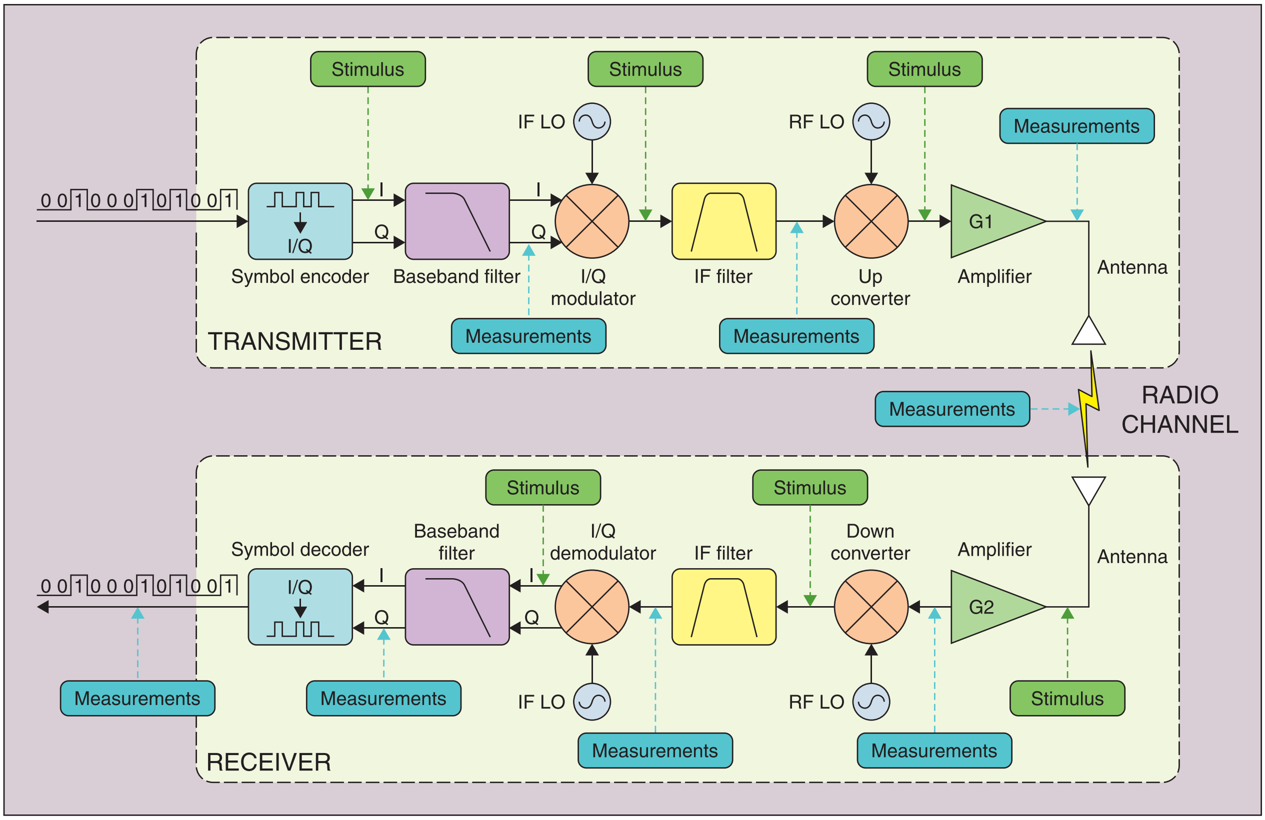

Fig. 2. Detailed architecture of a wireless communication system operating at radio frequency. It highlights typical points that correspond with either stimulus signals that are injected or measurements that are performed.

More specifically, the incoming serial bit stream is firstly converted by the symbol encoder in the corresponding I and Q baseband signals; each couple of I and Q values defines a proper symbol in the I/Q plane to be transmitted. To improve the spectral efficiency, the obtained I/Q signals are suitably baseband filtered before being shifted by the I/Q modulator either to intermediate frequency (IF) or RF. In the former case, a further bandpass IF filter is adopted before up converting the modulated signal to RF and transmitting it through a dedicated output amplifier.

The propagated RF signal impinges on the antenna of the receiver, whose implementation is very similar to the transmitter one. Just after the input amplifier, the incoming RF signal is first downconverted to IF, bandpass filtered and successively demodulated. As it can be expected, I/Q demodulation is the most error-prone operation, due to the number of possible sources of signal corruption (as an example, offending signal interference, atmospheric and/or electronic noise, signal multipath or fading, and so on). The last steps allow the restoration of the transmitted serial bit stream.

Relevant measurement points are highlighted in Fig. 2, each of which plays a specific role within the testing, performance assessment, and troubleshooting stages of the communication system. In particular, points referred to as *measurements* account for useful sections of the system, through which typical parameters can be evaluated, with the aim of testing the functionality or assessing the performance, or troubleshooting the preceding, as well as subsequent blocks. Points indicated as *stimulus*, instead, identify proper sections to be adopted to introduce into the chain some stimulus (physical) signals capable of emulating the ideal output of the previous blocks, to create the best operating conditions for the subsequent ones [2], [3].

As for the transmitter, most relevant measurements mainly involve the physical signal emitted at the antenna port. This is particularly true for performance assessment and troubleshooting issues. To this aim, an ideal receiver typically implements the corresponding measurement point [2], [4]. Differently, at the receiver side, most relevant measurements turn out to be those associated with the quality of the received information, in terms mainly of discrepancy of the restored bit stream from the nominal one originated by the transmitter. Measurement of proper parameters typically quantify the quality-of-service (QoS) level perceived by the final user. Troubleshooting issues are also dealt with [3], [4].

Table 1 – Two-dimensional taxonomy of the papers published in TIM in recent years according to the considered element of the communication system and the final measurement goal

<table>
<tr><th>Communication System Element</th><th colspan="5">Measurement Goal</th></tr>
<tr><td rowspan="2">Sender</td><td colspan="3">Performance Assessment</td><td colspan="2">Troubleshooting</td></tr>
<tr><td colspan="3">[8], [30], [33], [34], [37], [38]</td><td colspan="2">[35], [36]</td></tr>
<tr><td rowspan="3">Channel</td><td colspan="5">Propagation conditions</td></tr>
<tr><td>Power Line</td><td>Ethernet</td><td>Other wired</td><td>Wireless</td><td>Interference</td></tr>
<tr><td>[6], [18], [24]</td><td>[12], [26]</td><td>[16], [23], [31], [32]</td><td>[11], [19], [20], [29], [40], [41]</td><td>[42], [43], [44], [45], [46]</td></tr>
<tr><td rowspan="2">Receiver</td><td colspan="3">Quality-of-Service</td><td colspan="2">Troubleshooting</td></tr>
<tr><td colspan="3">[7], [9], [10], [14], [24], [25], [27]</td><td colspan="2">[13], [17], [18], [22], [28], [39]</td></tr>
</table>

Finally, if the channel is considered, most relevant measurements focus on the propagation conditions in the specific transmission media entailed, both in the time and frequency domain, thus taking into mainly account the physical communication signal (radiated signal in Fig.2) as well as potential interferers [2]-[5].

Current Trends and Applications

We conducted a comprehensive analysis of the papers on the considered topic published in TIM in recent years. A useful two-dimensional taxonomy has been arranged, according both to the considered element of the communication system (sender, channel, receiver) and the final measurement goal. Table 1 gives details.

It can be observed that the papers cover quite equally the different elements of the communication system, and, with special regard to the sender and receiver, the two different measurement goals. As for the papers dealing with measurements in the communication channel, a distinction occurs between wired (power line, Ethernet and others) and wireless transmission mediums. Papers addressing measurement issues arising from the interaction between useful and interfering signals have been also included under interference in Table 1.

Measurement in Communication Systems

As in any measurement, these main stages are required in measurements on communication systems:

- Modeling of the communication system, or more precisely, of all relevant entities in the experimental setting, i.e., the communication system with specific focus on the measurands and environment. The model is usually expressed in terms of the parameters adopted to characterize the performance of the communication system (e.g., BER, SNR, delay), and other quantities which might influence the measurement result (the so-called influence quantities) as well as their mutual relationships.
- Design of a measuring system that is capable of measuring the parameters of interest of the considered communication system. Usually, a suitable input signal must excite the communication system and the corresponding output signal is acquired and analyzed to estimate the system's performance parameters of interest. Measuring system design usually includes the definition of the input signal, the design of the output signal acquisition system and the design of the algorithm adopted to extract the parameters of interest from the acquired data.
- Data acquisition during measurement execution is performed according to the measurement procedure defined in the design stage, and raw measurement data are obtained. Then, information about the measurands is extracted from raw measurement data, usually by means of suitable digital signal processing and taking into account the information contained in the modelling phase. Also, measurement uncertainty is evaluated and expressed.
- In the interpretation stage, the measurement result is exploited to support decisions about communication system performance. A decision result could be, for instance, about system conformance or non-conformance, or it can be aimed at validating or improving the whole measurement procedure or the communication system itself.

It is worth noticing that some of the previous activities are not always accounted for in the scientific literature satisfactorily. For instance, a list of raw experimental results is provided without specifying the related measurement uncertainty. These results do not correctly support decision making activities (e.g., about performance of a novel measurement procedure), since the risk of wrong decision cannot be estimated without proper information on measurement uncertainty. Thus, evaluation and expression of measurement uncertainty is a very relevant task as we discuss in the next section.

Uncertainty Analysis

According to the most important reference documents in metrology, i.e., the *International Vocabulary of Metrology* (VIM) [46] and the *Guide to the Expression of Uncertainty in Measurement* (GUM) [47], measurement uncertainty is an essential part of any measurement results. The GUM defines measurement uncertainty as a "*parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand.*" To define uncertainty, the GUM assumes in clause 3.2.4 [47] that: "*the result of a measurement has been corrected for all recognized significant systematic effects and that every effort has been made to identify such effects.*" As a consequence, the only significant effects that remain are random and, consequently, a probability density function can be used to represent the dispersion of values that could reasonably be attributed to the measurand. In particular, the estimate of the related standard deviation called *standard uncertainty* is often employed to quantify measurement uncertainty.

According to the above fundamental concepts, the characterization of any measuring system adopted in communication systems must accomplish the following steps:

1. Identification and proper correction of all significant systematic effects; and
2. Expression of the possible dispersion of the provided measured values in terms of standard uncertainty.

When a novel measuring system or a part of it (e.g., a measurement algorithm) is proposed, the effects of the different sources of uncertainty must suitably be analyzed. Specifically, when different parts of the measuring system, both hardware components and algorithms, are expected to contribute to measurement uncertainty, steps 1 and 2 must be independently repeated for all of them, and the single standard uncertainty obtained must be properly combined [47] to achieve the overall combined standard uncertainty associated with the measurement result. This procedure is the only universally accepted approach to achieve the metrological characterization of measuring systems, and as such, it is an essential and unavoidable element of any novel measuring system component proposal.

Suitable measurement uncertainty analysis is also essential when measurement is performed to characterize the performance of a communication system. In this case, it is related not only to the measuring system but also to the model adopted to describe the communication system, or parts of it. Indeed, any model provides just a partial description of the entity it is representing, so that incomplete information about the considered communication system is always unavoidable.

A third kind of uncertainty source is the interaction uncertainty. It originates in the description of the interaction between the communication system and the measuring system, making the so-called loading effect rise. This kind of uncertainty source can be particularly significant at high frequencies, due to unavoidable capacitive behavior of measuring system inputs.

It is worth noticing that uncertainty analysis can be performed by using analytical approaches or simulations. Moreover, it should be validated by suitably processing data acquired from real-life systems.

Content of TIM Papers on Communication Systems

As stated by the IEEE I&M Society, TIM's scope encompasses research papers

> *that address innovative solutions to the development and use of electrical and electronic instruments and equipment to measure, monitor and/or record physical phenomena for the purpose of advancing measurement science, methods, functionality, and applications.*

Thus, the technical content of a paper submitted to TIM should clearly satisfy the above requirements, mainly by:

- presenting a prototype system or a fully developed system for which practical measurements can be made;
- performing a proper uncertainty analysis of the considered communication system or measuring system, or parts of them; and
- positioning the technical contribution of the paper with respect to the recent literature (and especially qualified international journals) in the field of I&M in the considered or related subjects, by comparing this contribution (by theory, simulation or experimental results) with existing state-of-the-art methods and techniques, highlighting its novelty and advancement.

Papers whose technical content falls outside the TIM's scope because their core contribution is strictly in communication, signal processing, automation, or electronic systems without significant I&M content are not acceptable for publication in TIM.

For example, a paper that proposes an algorithm that provides a more efficient parameter estimation technique, without properly characterizing its performance with respect to the related state-of-the-art in terms of contribution to measurement uncertainty in a GUM compliant way [46], is not considered aligned with the TIM's scope. Indeed, such a contribution should be directed to journals whose scope encompasses signal processing or communications subjects. Conversely, a paper that proposes a parameter estimation technique and then shows, maybe both with simulation and experimental results, that it is more accurate than state-of-the-art algorithms, is surely within the TIM's scope and of interest for TIM readers. Indeed, not just the proposal of new algorithms, but their performances such as output uncertainty, response time or computational efficiency, are of interest from an I&M perspective.

Conclusions

Communication systems are becoming more and more ubiquitous in our everyday lives, and instrumentation and measurement play a vital role in assuring their performance improvement. In this article, we give an overview of possible I&M technical contributions in this broad research field with the aim of providing useful guidelines to potential authors of papers to be submitted to the *IEEE Transactions on Instrumentation and Measurement*. In particular, we emphasize the fundamental role of suitable system modeling and uncertainty analysis.

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