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5G and IEEE 802.11

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ABOUT THE IEEE STANDARDS EDUCATION E-ZINE

Technical standards are formal documents that establish uniform engineering or technical criteria, methods, processes and practices developed through an accredited consensus process. The purpose of this publication is to help raise awareness of standards, show the importance of standards, present real-world applications of standards, and demonstrate the role you can play in the standards development process. Knowledge of standards and standards activities can help facilitate your professional engineering practice and improve technological developments to meet the needs and improve the lives of future generations.

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E-ZINE

Letter from the Editor

Oh Gee, 5G?

These days everyone is talking about 5G: 5G phones, 5G networks, 5G appliances, and even 5G-ready vehicular networks. So what is 5G? What is going to happen to my (flip) phone? My wireless router at home or an access point at my (small) office? My all-new electric car? Do I have to buy a whole new set of devices for my car, office, and home? Will my phone continue to work at Starbucks and at the airport with free Wi-Fi? Are there new standards coming up for these gadgets to work on the old and the new networks?

Even if you are a casual user of the internet looking for advances in communication technology, you will come across an alphabet soup (and numbers) with acronyms such as ITU-R, 802.11, 3GPP, IoT, .ad, and .ah. What about all the other TLAs (three-letter acronyms) I keep reading about in technical journals, magazines, and sometimes even the business media?

Well, you don't have to wonder anymore, nor do you have to wander very far. Adrian Stephens is a member of the Standards Education Committee (SEC) and the Editorial Board of this eZine. He is also very active in the wireless standards development community. In fact, he chairs the IEEE 802.11 working group. So, you are going to hear about these topics straight from the horse's mouth—literally!

Adrian has prepared a 15-minute video that explains the role of many of these standards, their respective organizations, and their interaction with each other. And at the end of his video talk, he introduces the other papers and articles. For many of our regular readers, Paul Nikolich's article will resonate well. Not only has he contributed to past eZines, but as the Chair of the entire IEEE 802 working group, he also has the best seat in the industry to tell you about the importance of standards in networks. Many of you will then move on to the focused articles and research papers to learn about these standards and related activities. We have a great collection from expert contributors:

Coexistence of Content-Centric Wireless Network (CCWN) and Traditional Cellular Networks, Bitan Banerjee, et al.
Interworking of mmWave and sub-6 GHz Access Technologies for 5G Multi-Connectivity, Kishor Chandra, et al.
Making 5G NR a Commercial Reality—A Unified, More Capable 5G Air Interface, Wanshi Chen
IEEE 5G Initiative Overview, Dr. Ashutosh Dutta
The Road Towards Faster, Simpler, and Smarter Test Equipment for mmWave Products, Dr. Jeorge S. Hurtarte
How IEEE 802.11 WLAN Is an Essential Part of a Practical 5G Cellular Network, Joseph Levy
5G Standards in IMT-2020 and Elsewhere, Roger Marks
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How Well-Positioned is IEEE 802.11ax to Meet the IMT-2020 Performance Requirements? Rakesh Taori and Farooq Khan

My special thanks to Adrian Stephens and Periklis Chatzimisios, members of the eZine editorial board, for reaching out to the 5G community and successfully soliciting this great collection.

For the past 18 months, we have engaged a few experts to help us understand the readership. IEEE staff member Robert Craig brings insight into the reader community we serve. Your comments, questions, and suggestions for future topics help us serve this community. Please let us know how we can help you reach this community with your work in standards education.

We are also privileged to share the experiences and insights of teaching standards in university curriculum by Prof. Hemchandra Shertukde, recipient of 2017 Standards Education Award.

Happy Reading …

Yatin Trivedi, Editor-in-Chief, is a member of the IEEE Standards Association Board of Governors (BoG) and Standards Education Committee (SEC), and serves as vice-chair for Design Automation Standards Committee (DASC) under Computer Society. Yatin served as the Standards Board representative to IEEE Education Activities Board (EAB) from 2012 until 2017. He also serves as the Chairman on the Board of Directors of the IEEE-ISTO.

Yatin currently serves as Associate Vice President for semiconductor design services at Aricent Inc. Prior to his current assignment, Yatin served as Director of Strategic Marketing at Synopsys where he was responsible for corporate-wide technical standards strategy. In 1992, Yatin co-founded Seva Technologies as one of the early Design Services companies in Silicon Valley. He co-authored the first book on Verilog HDL in 1990 and was the Editor of IEEE Std 1364-1995™ and IEEE Std 1364-2001™. He also started, managed and taught courses in VLSI Design Engineering curriculum at UC Santa Cruz extension (1990-2001). Yatin started his career at AMD and also worked at Sun Microsystems.

Yatin received his B.E. (Hons) EEE from BITS, Pilani and M.S. Computer Engineering from Case Western Reserve University. He is a Senior Member of the IEEE and a member of IEEE-HKN Honor Society.

Why are Standards of Value in Networks such as 5G?

by Paul Nikolich

The primary function of a network is to connect endpoints and allow information to flow between them. These endpoints can be humans or devices such as phones, tablets, sensors, automobiles, robots, drones, buildings, factories, etc. Ultimately, the number and type of endpoints are too numerous to list. Yet "the network" must connect them all, small and large, in a secure, reliable, consistent, and cost-effective manner. As a result, networks have grown into highly complicated systems that not only shuttle information around but also have the capability to monitor network health, automatically repair faults, measure usage, control access, and generate bills.

Today, these networks are assembled from a wide variety of components consisting of hardware and software elements that channel information along wireline cables and wireless channels. The functionality and interfaces of each component must be very well defined and specified in order to allow cabling suppliers, chip vendors, system vendors, network engineers, and communications service providers to interconnect them in a predictable and reliable manner. These specifications can be proprietary/custom or open/standard.

Furthermore, these components are sourced from a wide variety of suppliers that most likely do not have any formal interaction with one another. Yet these networks, built from an incredible array of components sourced from thousands of suppliers, work well and provide a high quality of service to their end users. How is this possible? It is because a rich library of performance and interface standards have been developed over the decades. These standards, which are agreed upon by the many standards development participants, are one of the primary reasons these networks operate so well. Networks will always be dependent on well-defined standards, whether they are created internally via a propriety process or cooperatively via an open, transparent and consensus process.

The open transparent and consensus process practiced by the IEEE 802 Local Area Network (LAN) / Metropolitan Area Network (MAN) Standards Committee has proven to be a successful model, as demonstrated by the economical delivery of Internet services worldwide based on components conforming to the specifications defined by the collection of IEEE 802 standards. The IEEE 802 family of standards is but one of many that have been developed by similar standard development organizations such as the International Engineering Task Force (IETF), CableLabs, International Telecommunication Union (ITU), and European Telecommunication Standards Institute (ETSI) – 3rd Generation Partnership Project (3GPP).

These standards enable networks to grow, and this growth creates marketplace volume efficiencies. These efficiencies result in lower costs, which encourage more use of the network, which enables new uses that may not have been economically viable in the past. This in turn drives the network service provider to further grow the network, resulting in the virtuous cycle we find ourselves in today. 5G is a buzzword that I don't care for much, but it has come to reflect that at a very high, gross level, networks are entering their next generation of growth. This growth has been partially but significantly fueled by the standards used to build almost every component, standards that networks conform to.

That's the value standards bring to 5G.

Paul Nikolich has been serving the data communications and broadband industries for roughly 17 years, developing technology, standards, and intellectual property and establishing new ventures as an executive consultant and angel investor. He is an IEEE Fellow and has served as Chairman of the IEEE 802 LAN/MAN Standards Committee since 2001. As 802 chairman, he provides oversight for 75 active 802 standards and the 50+ concurrent 802 activities in wired and wireless communications networking. 802 has over 750 active members and manages relationships between IEEE 802 and global/regional standards bodies such as ISO, ITU, and ETSI, regulatory bodies, and industry alliances. He is a member of the IEEE Computer Society Standards Activities Board and is an active leader in IEEE, the IEEE Computer Society, and the IEEE Standards Association.

He is a partner in YAS Broadband Friends, LLC, and holds several patents. He serves on the boards of directors and technology advisory boards of companies developing emerging communications technology along with being a board member of the University of New Hampshire's Broadband Center of Excellence. Mr. Nikolich has held technical leadership positions at large and small networking and technology companies (e.g., Broadband Access Systems, Racal-Datacom, Applitek, Motorola, and Analogic). In 1978–1979, he received a B.S. in electrical engineering, a B.S. in biology, and an M.S. in biomedical engineering from Polytechnic University in Brooklyn, NY, USA (now the NYU Tandon School of Engineering).

How IEEE 802.11 WLAN is an essential part of a practical 5G celluar network

by Joseph Levy

This article provides some high-level architectural descriptions of a fifth-generation (5G) cellular network that contains an IEEE 802.11 wireless local area network (WLAN). There is no agreed-upon definition of what a 5G network is as various stakeholders have different definitions based on their perspectives. The Third Generation Partnership Project (3GPP), the cellular standardization community, defines 5G to mean the next generation of cellular technology (3GPP Release 14, 15, and 16 specifications). These releases are the specifications that 3GPP is developing to address the International Telecommunications Union Radiocommunication Sector's (ITU-R) International Mobile Telecommunications 2020 (IMT-2020) requirements [1]. The general IEEE community has embraced a definition of 5G to be the advanced/next-generation communication technologies that will contribute to defining next-generation networks [2]. To the cellular marketing community and the general public, it has been defined as the next advance in communications technology, following 4G (Long Term Evolution, LTE), which will "improve" everyone's life. For this article, the 5G cellular network is understood to be the next generation network that will provide communications services for mobile devices: smartphones, tablets, and laptops. To connect these devices, it is assumed that the network will need to include multiple radio access technologies (RATs) such as IEEE 802.11-based WLAN (802.11) [9], commercially known as Wi-Fi and WiGig, and various 3GPP-defined wireless cellular technologies such as Enhanced Long-Term Evolution (eLTE) and New Radio (NR).

Please note that the example network architectures provided in this article are used to illustrate different ways of implementing an integrated 5G network. This set of examples is not intended to be complete, and actual implementations will vary as they will be customized to the network operator's business and customer needs.

Many user applications and services need to have connectivity between the mobile device and application or service servers in order to function. Network technologies and radio access technologies (RATs) provide this connectivity by defining data bearers for these applications and services to use. The architectures described below manage and assign RAT resources to these bearers differently and, therefore, may have different efficiencies, flexibilities, and dynamic performances. However, they all attempt to achieve the same end goal of providing data bearers to meet user needs.

It is also assumed that the 5G network will provide data bearers that will connect mobile devices to various applications and services. These data bearers will use a RAT or multiple RATs connected to a 5G core network or a general wide area network (WAN) to provide these connections. The architectures shown are consistent with the planned 3GPP Release 15 specifications (June 2018) [1], [3], and [4]. To enhance the connectivity options of the 5G cellular network an IEEE 802.11 based WLAN is added. The inclusion of an IEEE 802.11-based WLAN is currently a reality in many existing 4G cellular networks as Wi-Fi-based internet browsing, video streaming, and Wi-Fi calling are usually available to users with most mobile devices. It is also assumed that the 3GPP user equipment (UE) shown in the diagrams can support multiple RATs simultaneously (e.g., eLTE, NR, and Wi-Fi).

1. The first architecture connects the mobile device to the 5G core network by any or all of the three available RATs: eLTE, NR, or 802.11, as shown in Fig. 1. The 5G core network provides connectivity to application and service servers. In this architecture, the 5G core network is connected through the eLTE RAT, which then manages the data flows (solid line connections) over all the RATs: eLTE, NR, and 802.11. The eLTE Node B performs the bearer management to route the data to and from the mobile device through a RAT or combination of RATs. For data being sent via the 802.11 RAT the Node B can use the 3GPP specified LTE-WAN Aggregation (LWA) [5], [6] or LTE WLAN Radio Level Integration with IPsec Tunnel (LWIP) [4], [5] capabilities. Routing of data via the NR RAT is part of the planned 3GPP Release 15 specifications [1]. This architecture allows the eLTE Node B to make near "real time" splitting and routing decisions based on link performance of the available RATs. All non-access stratum (NAS) control signaling (dashed connection) is sent over the eLTE RAT. Note that there have been some discussions regarding 3GPP LWA/LWIP type aggregation for 3GPP NR. However, at this time, there is no 3GPP activity to create such a specification, though it may be considered in the future by 3GPP Technical Specifications Group (TSG) on Radio Access Network (RAN) [3]. If this 3GPP NR capability is specified, it will enable an alternate architecture where the NR Node B manages the aggradation of the RATs and provides the NAS control signaling. This alternative architecture will connect the 5G core network directly to the NR RAT (and not the eLTE RAT).

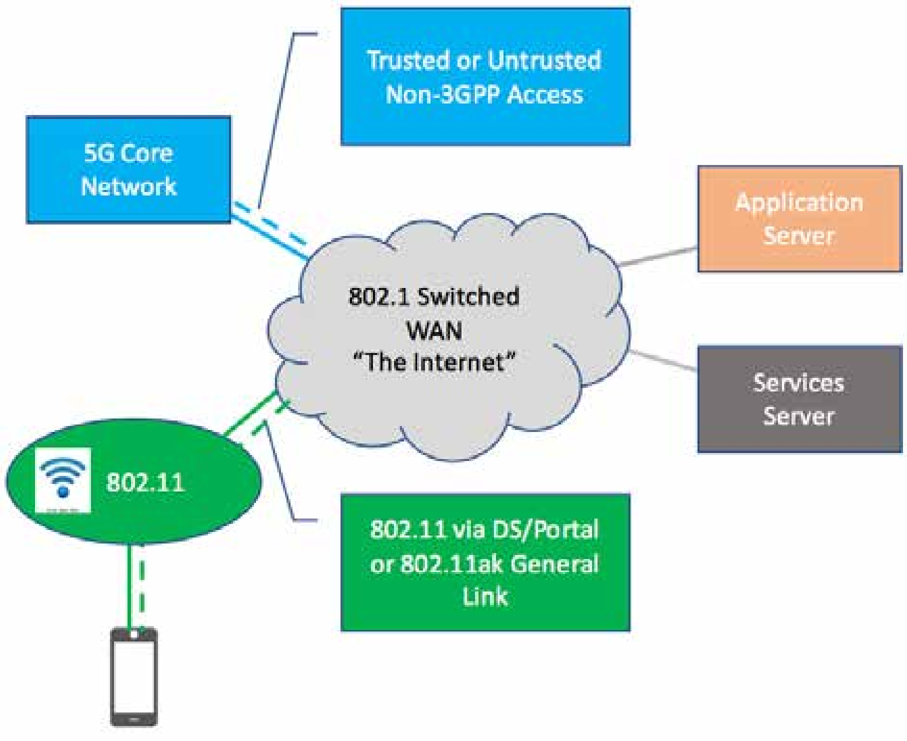

Fig. 3. IEEE 802.11-connected mobile device connecting to the 5G core network and other services.

2. 3GPP TSG, Service and Systems Aspects (SA) is currently working to define a set of specifications for the 3GPP 5G system that will specify a common interface between the access network and the core network. This interface will integrate both 3GPP and non-3GPP access types [4], [8]. In this architecture, the 802.11 RAT is connected directly to the 3GPP 5G core network via a trusted or untrusted non-3GPP interface. The trusted or untrusted non-3GPP interface is currently being specified by 3GPP TSG SA [4]. As shown in Fig. 2, data bearers are routed or split by the core network over any or all the available RATs: eLTE, NT, and/or 802.11. This architecture allows the core network to optimize the data flows to and from UEs. Control is shown to be provided via the NR access network, which is one probable configuration as the control signaling routing is also configurable by the 5G core network.

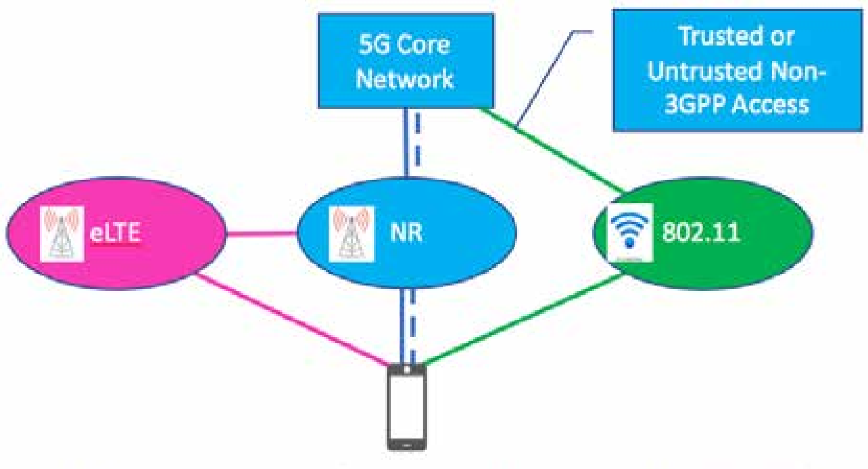

Fig. 2. 3GPP 5G core integration of an eLTE RAT, an NR RAT, and an 802.11 WLAN network.

3. In the third basic architecture, shown in Fig. 3, a mobile device is connected through a single RAT, 802.11, to an 802.1 switched WAN that provides network connections to an application server, a service server, and a 5G core network (which may provide connectivity to additional application and service servers, not shown). The 802.11 wireless network can be connected to the WAN via a traditional 802.11 distribution service (DS) and a portal combination [9] or by a direct connection to an IEEE Std 802.1Q bridge [11], [12] via an 802.11 general link [10]. To allow applications and services accessible though the 5G core network, a connection to the 5G core network is provided via 3GPP-defined untrusted or trusted non-3GPP access [4], [8]. The bearers in this architecture are managed by the WAN management of packet flows through the network and/or the 3GPP 5G core network. Note that most UEs currently use a variation of this architecture to browse the internet, stream videos, and provide Wi-Fi calling when they are connected to the internet via Wi-Fi.

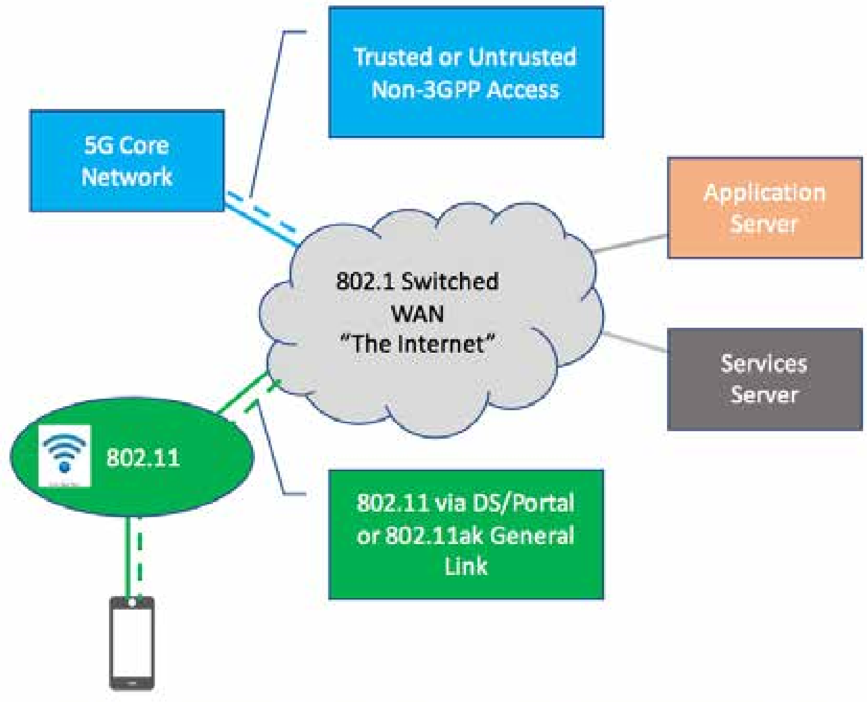

Fig. 3. IEEE 802.11-connected mobile device connecting to the 5G core network and other services.

The high-level architectures described provide an overview as to how 5G networks may be configured to leverage existing and future IEEE 802.11 WLAN RATs with existing LTE RATs and future eLTE/NR RATs so that the 5G goal of an always-on, high-speed wireless access network to support user applications and services on mobile devices can be met. To achieve this goal, it is essential to use both current and future deployed RATs and networks. Given the large and ever-growing number of installed IEEE 802.11 WLANs and the almost universal availability of 802.11 RAT in mobile devices, it is desirable to leverage these RATs to enable the deployment of 5G networks in a timely and cost-effective manner.

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Joseph Levy is with InterDigital, Inc. He is Chair of IEEE 802.11 AANI.

5G Standards in IMT-2020 and elsewhere

by Roger Marks

What is 5G? Who knows?

In my observation, a most frequently asked question of the last few years, not only in the fields of telecommunications or standardization, has been "What is 5G?" One web search turns up about 73,000 matches for that phrase. Yet a brief literature survey indicates that the number of answers may be of the same order of magnitude as the number of times the question has been asked. This brief article does not attempt to answer the question in depth but simply provides a perspective.

Gs and re-Gs

5G is intended to represent something beyond 4G, which followed 3G and indicates the fourth generation of cellular wireless network technology. Earlier generations of cellular were identified in retrospect as 1G and 2G, but those monikers were not popular at the time. However, the industry focused on the term "3G", and it became a hit, spawning a successful sequel in 4G.

Many technology industries evolve, but not all with the discrete cadence of the cellular industry. That business is heavily dependent on interoperability, and the various facets of the industry—including components and devices, software and networks, engineering expertise and marketing—are all orchestrated in a worldwide symphony. Cellular operators, which are limited in number, stable over many years, and often strong players in their markets, coordinate closely with a relatively small community of major vendors to steer the technical and market evolution. This evolution is mediated by standardization, particularly through the 3rd Generation Partnership Project (3GPP), a partnership of regional standards-developing organizations that has retained its original name while its focus has turned toward successive generations.

Regulatory mediation

The rollout of new cellular standards is not only tied to industry coordination but also tightly bound by international regulations. National-scale cellular providers operate using radio spectrum that is exclusively licensed for their use by national administrations. Global harmonization and global circulation of mobile devices that operate in such restricted radio bands hinge not only on technical standards but on compatible regulatory environments. The key international requirements are laid out in the Radio Regulations hammered out in a series of World Radiocommunication Conferences (WRCs) of the Radiocommunication Sector (ITU-R) of the United Nations' International Telecommunication Union (ITU). Much of the content of the Radio Regulations is technologically neutral. However, in the 1990s, the ITU Radio Regulations began to "identify" spectrum for potential use by "International Mobile Telecommunications (IMT)," where IMT is specified by a series of ITU "Recommendations," which are standards. This "identification" is not a mandatory aspect of the Radio Regulations; identification is "for those administrations wishing to deploy IMT" and is intended to provide guidance for regulators and global equipment manufacturers regarding appropriate radio bands and technologies. The combination has proven very effective in providing guidance to the industry and has been successful beyond any parallel in the history of technology.

As the industry has succeeded, it has, time and again, faced the need for more spectrum in which to operate. Long-term spectrum demand has been channeled into a series of requests for additional spectrum for modernized technology. Roughly once per decade, the cellular industry and ITU have formulated the concept of a new generation of technology that promises greater opportunity and is accompanied by additional spectrum identification. In 2000, significant spectrum was identified for technology and was specified as "IMT-2000" in ITU-R Recommendation M.1457. That recommendation incorporates external standards, such as those of 3GPP, and these are identified through the unique IMT concept of "Global Core Specifications." Through an IMT-specific activity (currently known as ITU-R Working Party 5D), Rec. M.1457 has been maintained and updated annually or biennially, pointing to evolving 3GPP specifications as well as some others.

IMT-Advanced

Although various technology alternatives were adopted in IMT-2000, the most striking technology thread was multiple access via CDMA. As the decade proceeded, ITU-R undertook the development of a new generation of IMT, known as "IMT-Advanced," and began intensive discussion on identification of additional IMT spectrum. Meanwhile, alternative technologies rose to prominence, particularly suited to the increasing demands for broadband data services. In the IEEE 802 LAN/MAN Standards Committee, IEEE Std 802.11 introduced OFDM in 1999. This became very successful in the marketplace, particularly beginning with the 802.11g amendment in 2003. IEEE Std 802.16 pioneered the use of OFDMA for broadband wireless access, notably with IEEE Std 802.16e-2005, which was deployed by commercial cellular operators in several countries. That WirelessMAN-OFDMA technology was adopted into IMT-2000 in 2007. In 2006, IEEE 802 authorized a new project with the specific target of meeting the IMT-Advanced requirements. The result, later published as WirelessMAN-Advanced in 802.16m-2011, was one of two technologies (both OFDMA-based) incorporated into IMT-Advanced in ITU-R Rec. M.2012. However, WirelessMAN-Advanced was not deployed in the cellular market, losing out to 3GPP's LTE.

ITU-R approached the new technology by broadening the concept of IMT to include IMT-2000 and IMT-Advanced (which would both continue to evolve) as well as additional varieties of IMT to be developed in the future. The 2012 WRC identified additional spectrum for IMT, replacing "IMT-2000" with the more general term "IMT" so as not to connect specific spectrum to specific versions. Just before the 2015 WRC, the ITU Radiocommunication Assembly nonetheless added IMT-2020 to the lexicon as the next evolution under the IMT umbrella.

What is 4G?

Before we all began asking what 5G is, this same question arose regarding 4G.

OFDMA was the striking common technology thread in IMT-Advanced and denoted a major demarcation of a new generation. It was, and remains, technically appropriate to identify the OFDMA technology as the mark of 4G. Still, as noted, OFDMA had found its way into evolutions of IMT-2000, and opinions varied as to how closely the meaning of 4G should be tied to IMT-Advanced.

Even ITU struggled with the distinction between 4G and IMT-Advanced. During the development of the work, ITU-R Working Party 5D had explicitly decided not to use the term "4G." However, in a 2010 press release announcing IMT-Advanced, ITU-R said that "LTE-Advanced" and "WirelessMAN-Advanced" were "accorded the official designation of IMT-Advanced, qualifying them as true 4G technologies" [1]. This stance conflicted with commercial identification of LTE and WirelessMAN (and even some updated CDMA-based) technologies as 4G. Indeed, even in 2018, many LTE implementations lacking the suite of LTE-Advanced features are recognized by industry and the public as 4G. ITU soon quietly backed off its stance that IMT-Advanced was the mark of true 4G. Currently, ITU states that "The term '4G' remains undefined… ITU cannot hold a position on whether or not a given technology is labelled with that term for marketing purposes" [2].

The perspective of this article is that the Gs are not standardized terms or certification marks, and neither the ITU nor any other entity establishes their requirements. Most IMT-2000 technologies can be characterized as 3G or higher, and the IMT-Advanced technologies can be characterized as 4G or higher. However, the terminology is loosely used, even within the cellular industry, and no entity determines the official definition. ITU recognition provides a sound credential for a G claim, but technologies not in any way represented in ITU may nevertheless be fairly identified with a G.

IMT-2020

ITU-R began planning for IMT-2020 in 2012, and a set of Recommendations and Reports were prepared by Working Party 5D, including the vision, framework, and objectives document (Rec. ITU-R M.2083) that was referenced by WRC 2015. This activity resulted in some new signals about 5G trends. In particular, as a follow-up to WRC 2015, an agenda item (1.13) was added to WRC 2019 to consider identification of spectrum for IMT in a number of higher-frequency bands ranging from around 24 to 86 GHz, signaling that IMT-2020 is partially related to millimeter-wave radio. Further, Rec. ITU-R M.2083 indicated a much wider range of applications as compared to prior versions of IMT. In particular, IMT-2020 will be specified to address three "usage scenarios":

1. enhanced mobile broadband (eMBB), extending the services provided by IMT-Advanced;

2. ultra-reliable and low-latency communications (URLLC), addressing applications such as industrial manufacturing, remote surgery, and controlled automobiles;

3. massive machine type communications (mMTC), considering a very large number of low-cost, low-energy devices typically transmitting a relatively low volume of non-delay-sensitive data.

These decisions indicated an intention to drastically expand the scope of IMT and, therefore, the breadth of applications to be supported within IMT-identified spectrum. This could be broadly understood to represent the notion that the cellular communications industry, including the operators and vendors, would expand their business beyond a focus on supporting handheld devices.

ITU-R has completed follow-up documentation specifying the IMT-2020 development process, schedule, technical requirements, and evaluation criteria, setting a proposal deadline of June 2019 and planning to complete the IMT-2020 Recommendation by October 2020. 3GPP has already provided information regarding its intended submission.

The IMT-2020 requirements spell out an ambitious and challenging program for the cellular industry that certainly will demand many technical advances. If the current generation is 4G, then IMT-2020 invokes a new view of 5G or beyond. However, unlike 3G and 4G, which could be understood as embodying specific technologies, IMT-2020 is positioned as an application-expanding effort involving optimization of technologies in a variety of environments.

What else is 5G?

The vision of enhanced mobile broadband and an expanded set of wireless applications has stimulated not only the cellular industry but others as well. Some of the ambitions are individual and others are standardization based.

Within the IEEE, many activities relevant to 5G have arisen. IEEE has organized a coordination of those efforts as the "IEEE 5G" Initiative [3]. Many technical activities and fields of interest are represented there. The website identifies 5G as "next generation networking," which is clearly much broader than IMT-2020. The initiative compiles the "IEEE 5G and Beyond Standards Database" and supports an "IEEE 5G Roadmap" activity as well.

5G cannot be contained within ITU or any specific control group. Any endeavor that relates to a "generation" must represent some level of coordination of technologies and timeframes. A credible 5G will represent an integrated network specification set that could support a large operator deployment, be stable for the long haul, will support multiple applications and access technologies, and will evolve [4].

Outside the IEEE, other visions of 5G have been articulated. For example, CableLabs [5] has envisioned 5G wireless from the cable telecommunications industry perspective and sees IEEE and Wi-Fi technology standards as part of "the essential core of 5G."

The Final G?

Technology industries typically evolve based on technical innovations that are driven from the bottom up, by new discoveries and newly practical implementations. The concept of a decade-long coordinated effort to plan and push out a new technology generation worldwide is an exceptional case. 3G and 4G cellular, and perhaps 5G cellular as well, are ideal examples of the exception. However, while 3G and 4G were focused on specific deployment scenarios—communicating to human beings via handheld devices—5G is anticipating a much broader role. With this broadened focus, it is difficult to envision 5G as a coherent set of products and services. As a result, it is easy to imagine that the variety of differentiated scenarios will fracture the market into a set of differentiated industries with separate players, business models, and cost structures. As a result, the upgrade timescales of those industries may vary as well. It may be difficult to coordinate those disparate industries with the kind of singular focus required to integrate global technology innovations into a decade-long mass action. As a result, 5G may be the last of a royal lineage.

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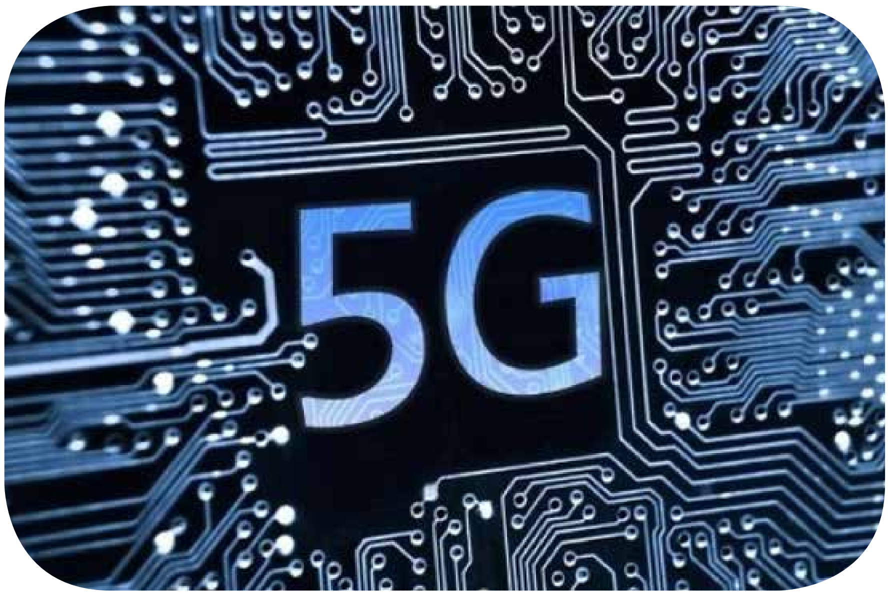
Making 5G NR a commercial reality - a unified, more capable 5G AIR interface

by Wanshi Chen



There is insatiable demand for mobile broadband. In December 2017, as part of 3GPP's Release 15, a first version of 5G new radio (NR) was declared complete. The first version is a non-standalone (NSA) version where a 5G NR carrier leverages 4G LTE for coverage and mobility while enabling a fast introduction of 5G NR to enhance user plane performance and efficiency. The standalone version of 5G NR is expected to be ready by June 2018.

5G NR is essential for next generation mobile experiences, providing fiber-like data speeds, low latency for real-time interactivity, more consistent performance, and massive capacity for unlimited data. In addition, 5G expands the mobile ecosystem to new industries. It provides diverse services including traditional enhanced mobile broadband (eMBB), new verticals such as massive machine-type communications (mMTC), ultra-reliable low-latency communications (URLLC), and cellular vehicle-to-everything (C-V2X), and scalability to address a tremendous variety of requirements. It covers diverse spectra, including sub-6 GHz and millimeter wave (mmWave), in order to get the most out of a wide array of spectrum bands/types. It also supports various deployments, from macro to indoor hotspots, with support for a range of topologies.

The first version of 5G NR establishes the foundation for 5G NR eMBB and beyond and employs a set of key enabling techniques. These include:

- A scalable Orthogonal Frequency-Division Multiplexing-based air interface, with subcarrier tone spacing ranging from 15 kHz to 240 kHz. It can efficiently address diverse spectra, deployments, and services while reducing FFT processing complexity for wider bandwidths with reusable hardware.
- A flexible slot-based framework, necessary for low latency, URLLC, and forward compatibility. In particular, it introduces a self-contained slot structure with the ability to independently manage resources on a per-slot basis and avoid static timing relationships across slots. The duration of a slot is also salable (e.g., 1 ms, 0.5 ms, 0.25 ms, 0.125 ms) in order to accommodate diverse latency/QoS requirements. One example of a slot type is a time-division-duplex-like self-contained slot where a single slot may provide opportunities for downlink and uplink scheduling, data, HARQ response, and uplink sounding. Another example is a data-centric slot (e.g., a downlink or an uplink data-only slot). A slot may also contain a mini-slot optimized for shorter data transmissions (e.g., URLLC). It is also possible to have a blank slot, which is designed to facilitate future feature introductions.
- Advanced channel coding. LDPC is used for 5G NR data channels, providing high efficiency with significant gains over 4G LTE Turbo encoding, particularly for large block sizes suitable for eMBB. It brings low complexity and enables an easily parallelizable decoder scaled to achieve high throughput. In addition, it offers low latency, where efficient encoding/decoding enables shorter transmission time at high throughput. For downlink and uplink control channels, Polar coding has been adopted, which gives reliable control channel transmissions.
- Massive MIMO, a key enabler for utilizing higher spectrum bands such as 4 GHz with existing 4G LTE sites. 5G NR is optimized for TDD reciprocity procedures using uplink sound reference signals. It further enhances channel state information-reference signal (CSI-RS) design and reporting mechanisms compared with that of 4G LTE. It also employs advanced high-spatial resolution codebook supporting up to 256 antennas.
- Mobilizing mmWave. mmWave is the new frontier of mobile broadband, with wide bandwidths (e.g., 400 MHz for a carrier) for extreme capacity and throughput. Beamforming and beam-tracking are essential for mobilizing mmWave. Innovations in 5G NR overcome challenges such as significant path loss in bands above 24 GHz, mmWave blockage from objects like hands, bodies, walls, and foliage, and fitting mmWave design in smartphone form factor and thermal constraints. 5G NR enables mmWave to be deployed with very dense network topology and spatial reuse (~150–200 m inter-site distance). 5G NR also supports the tight integration of mmWave with sub-6 GHz carrier frequencies.

For the next steps, many new additional features are expected to be further investigated and specified in 5G NR. 5G NR will provide more dedicated support for URLLC services (e.g., a reliability level of up to 10-5 block error rate (BLER) subject to a 1 ms delay budget). While LTE C-V2X supports both basic and some enhanced safety, 5G NR for

C-V2X is expected to bring higher throughput, higher reliability, wideband ranging and positioning, and lower latency, which will eventually enable new capabilities for the connected vehicle, such as sensor sharing, intention/trajectory sharing, wideband ranging and positioning, local high definition, and maps/"bird's eye view." 5G NR is also studying the possibility of further enhancing the support of the massive Internet of Things via non-orthogonal multiple access (NOMA). In addition to the licensed spectrum, it is important to investigate 5G NR operation in both unlicensed and shared spectra, valuable for a wide range of deployments such as aggregation with licensed spectra, enhanced local broadband services, and private 5G networks. Integrated Access and Backhaul (IAB) is also being studied for cost-efficient dense deployments to improve coverage and capacity while limiting backhaul cost. There are also many other features under consideration, including enhanced broadcast, non-terrestrial networks, and flexible duplex.

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Wanshi Chen has over 17 years of experiences in telecommunications in leading telecom companies including operators, infrastructure vendors, anduser equipment vendors. From 2006, he has been with Qualcomm Corporate R&D contributing to system design, prototyping and implementation, and standardization of 4G LTE/LTE-Advanced and more recently 5G (New Radio or NR). He has been attending 3GPP TSG RAN1 for over 10 years, representing Qualcomm and playing an instrumental role in 4G and 5G standardization, as a Vice Chairman from August 2013 for 4 years, and as Chairman starting from August 2017. From 2000 to 2006, he worked at Ericsson, San Diego, responsible for 3GPP2 related system design, integration, and standardization. During 1996 and 1997, he worked as an engineer for China Mobile, primarily participated in wireless network maintenance and performance optimization. Wanshi Chen is a recipient of Qualcomm's IP Excellence Award, Upendra Patel Achievement Awards for Outstanding Contributions to LTE, and Super Qualstar Award from Qualcomm CR&D. The highest degree that Wanshi Chen has received is a Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles, CA, USA. Wanshi is an avid runner. He ran the Boston Marathon in April 2017 with a time of 3 hours and 8 minutes.

IEEE 5G Initiative Overview

by Dr. Ashutosh Dutta

The IEEE 5G Initiative was launched by the IEEE Future Directions Committee on August 29, 2016, in Princeton, NJ, USA. Currently there are 21 IEEE societies contributing to this initiative.

The primary objectives of the IEEE 5G and Beyond Initiative are as follows:

- Foster collaboration and connect technical and business communities to IEEE 5G experts and resources;
- Act as the catalyst for IEEE cross-society activities on 5G;
- Establish IEEE as a thought leader essential to the 5G community;
- Be recognized as the go-to resource for engineering and technology professionals in industry, academia, and government working on 5G;
- Develop and promote valued programs, products, and services for the 5G community;
- Present a single IEEE face/voice to the 5G marketplace;
- Be a true global 5G initiative, capturing the needs of all global regions;
- Create a neutral platform/forum where those interested in 5G can engage and collaborate.

IEEE 5G Initiative

Ashutosh Dutta, AT&T, Co-Chair
Gerhard Fettweis, Technical University of Dresden, Co
Harold Tepper, Senior Program Director

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The IEEE 5G and Beyond Initiative is governed by a steering committee that includes steering committee co-chairs, representatives from contributing societies, and co-chairs from various working groups, namely Standards, Education, Publication, Conferences, Content Development, Community Development, Industry Outreach, and Technology Roadmap. Each of these working groups consists of a committee of 10–20 members chaired by two working group co-chairs. Similarly, the Technology Roadmap Working Group consists of nine focused technical working groups: Standardization, MIMO, mmWave, Hardware, Security, Edge Automation Platform, Applications, Satellite, and Testbed. More details about the IEEE 5G and Beyond Initiative, including how one can contribute, can be found at 5g.ieee.org.

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Coexistence of Content-Centric Wireless Network (CCWN) and Traditional Cellular Networks

by Bitan Banerjee, Sibendu Paul and Amitava Mukherjee

Abstract—Enabling content-centric network (CCN) features over a cellular network can significantly reduce mobile data traffic and support upcoming 5G. However, traditional cellular networks follow a host-centric network architecture rather than the content-centric architecture. Moreover, supporting CCNspecific features, such as multicast and broadcast of a content to multiple users, searching a possible content source in a wireless environment is extremely challenging due to constraints of limited power and user mobility. The primary question remains, how to distinguish between CCN packets and normal cellular network packets? Is it possible to enable this features at router level? In this article we explore several technologies and packet formats to support coexistence of CCWN and traditional cellular communication.

I. INTRODUCTION

Annual mobile traffic is growing exponentially and suggestively the growth rate was 63\% [1] in 2016. Rapid proliferation of tablets and mobile devices suggest even greater future growth prospects but finiteness of the radio spectrum forwireless communication makes it highly challenging to regulate exabytes of data traffic successfully. Various innovative technologies are being developed to support the traffic, and cache enabled content centric networking is one of the most promising technologies [2]. Video delivery companies (e.g., YouTube, Netflix) already use simple forms of popularity based in-network caching in today's Internet to improve user performance. These video delivery applications primarily determine the popularity of multimedia content based on parameters such as release date, viewership of past series of a show and push popular content to the network edge [3]. Recent performance analysis works for content centric networking (CCN) suggest that caching popular content within the network significantly improves network's performance.

Typically, CCN is a multicast enabled architecture, where multiple users requesting the same content are served together from a nearby cache instead of the original content server. Multicast manner for content distribution is a simple method to alleviate traffic load in both network and content sender regardless the number of receivers. Moreover, multicast routing features the following relevant aspects.

- Data is pushed to receivers, supporting multiple transport streams in parallel and eliminating the need to ask for content changes.
- Data distribution supports immediate in-network forwarding and is suitable for efficient, scalable real-time streaming in particular. This mainly covers the use case of real-time date dissemination without storage or caching requirements.
- The multicast model contributes many-to-many communication, which is valuable whenever information is created at distributed origins. Multisource communication using a single name faces strong conceptual difficulties in unicast-based CCNs.
- Multicast group communication enables rendezvous processes, as publishers and subscribers remain decoupled and unknown to each other.

Although multicast feature of CCN is extensively explored in literature [4], [5], combination of CCN and multicast scheme in a cellular network is remains a bottleneck because wireless multicast scheme at MAC does not guarantee complete packet delivery [4]. Moreover, distinguishing IP traffic and CCN traffic, i.e., differentiating a CCN packet and a traditional IP packet at network level is a challenging problem for future coexistence of CCN and wireless cellular network. Therefore, in this article we explore how to standardize multicast routing and multiplex CCN and IP network features in a cellular network.

A. Paper Organization

The rest of the paper is organized as follows. We provide an overview of existing coexistence problems in Section \ref{coexist}. Network architecture and different features of CCWN is discussed in Section \ref{net_arch}. Thereafter, we propose some of the possible technologies to support the coexistence. Finally we conclude the article with open research problems and future directions

II. COEXISTENCE PROBLEMS ARE NOT NEW

Coexistence challenges in communications and networking are present from the very beginning of standard transitions. At outset, the inevitable transition from IPv4 to IPv6 to avoid the IP address exhaustion and routing scalability employs the IPv4/IPv6 coexistence [6], [7]. Initially IPv6 was designed with no backward compatibility with IPv4, but the vast network resources and services were still using the IPv4. Hence, IPv4 and IPv6 will coexist for a longer period. To achieve this heterogeneous traversal, principles of tunneling was introduced [8]. To deliver IPv4 packets over IPv6 network in the middle, first, we need to encapsulate IPv4 packet into the new IPv6 payload then again at the next tunneling endpoint, we need to decapsulate it to get back the IPv4 packet.

Similarly, coexistence problem is also observed between Long Term Evolution (LTE) from 3GPP and WiFi. It came to picture when LTE had to expand to the unlicensed bands between 2.4-5 GHz to support export exponential growth of mobile users, and incidentally these were the unlicensed bands where WiFi channels were allocated previously [9]. The fair and friendly LTE-WiFi coexistence can be achieved by deploying new protocols e.g. LTE Unlicensed (LTE-U) and Licensed-Assisted Access (LTE-LAA). The first one uses the duty cycle-based approach and carrier aggregation where the latter one uses listen before talk (LBT) [10], [11].

In this proceeding, the coexistence of TCP-IP with the Information-Centric Networking protocol (CCN) also imposes a major issue for carrying TCP traffic over CCN transparently. In order achieve a fair coexistence, a protocol translation along with tunneling have been proposed [8]. Tunneling will aid to encapsulate TCP segments to interest packets or decapsulate from data packets. On the other hand, protocol translation helps to coexist the functionalities of pull-based CCN and push-based TCP model.

Basic methodologies used to attain a fair coexistence between a newly adapted technology and already available cellular technologies are an introduction of inter-proxy protocols in order to make two technologies synchronized without having any interference or collision, and most importantly disrupting and users experience.

III. NETWORK ARCHITECTURE

The architecture of a typical wireless cache-enabled network is illustrated in Fig. 1. At the bottom of the hierarchy, there are access points with smaller coverage area, called eNodeB. From CCN point of view eNodeBs can be called edge caches, which are connected with the users over a wireless medium. SBSs are connected to to the servers via a multilayered backbone network. The backbone network consists of wired routers, termed core caches. Now depending on the user activity, cellular data traffic from Macro BS or enodeBs can be IP based or CCN traffic. If the content is available at another user or eNodeB, then request is generally routed to that node, thus leading to D2D and M2M communication. Therefore, M2M, D2D communications and communication of WiFiAP in the unlicensed band coexist along with this. Now IP requests and CCN requests that are not served by a edge cache is aggregated at the aggregator.

A question immediately comes to mind, how to packetize CCN requests and CCN related traffic in traditional IPv4 and IPv6 to aggregate all of them together using aggregator? In next section we will discuss possible solutions for this challenge. FOr the time being let us assume that CCN requests can be encapsulated in a IP packet. Now all the aggregated IP data-traffic not found in edge routers or nearby server, is searched in the interconnection of routers in the IP network following the shortest path algorithm. Here efficient caching and routing mechanism are extremely important to properly utilize the network caches. A comprehensive study of caching strategies is discussed in [12], and a study of routing and content naming strategies is discussed in [13].

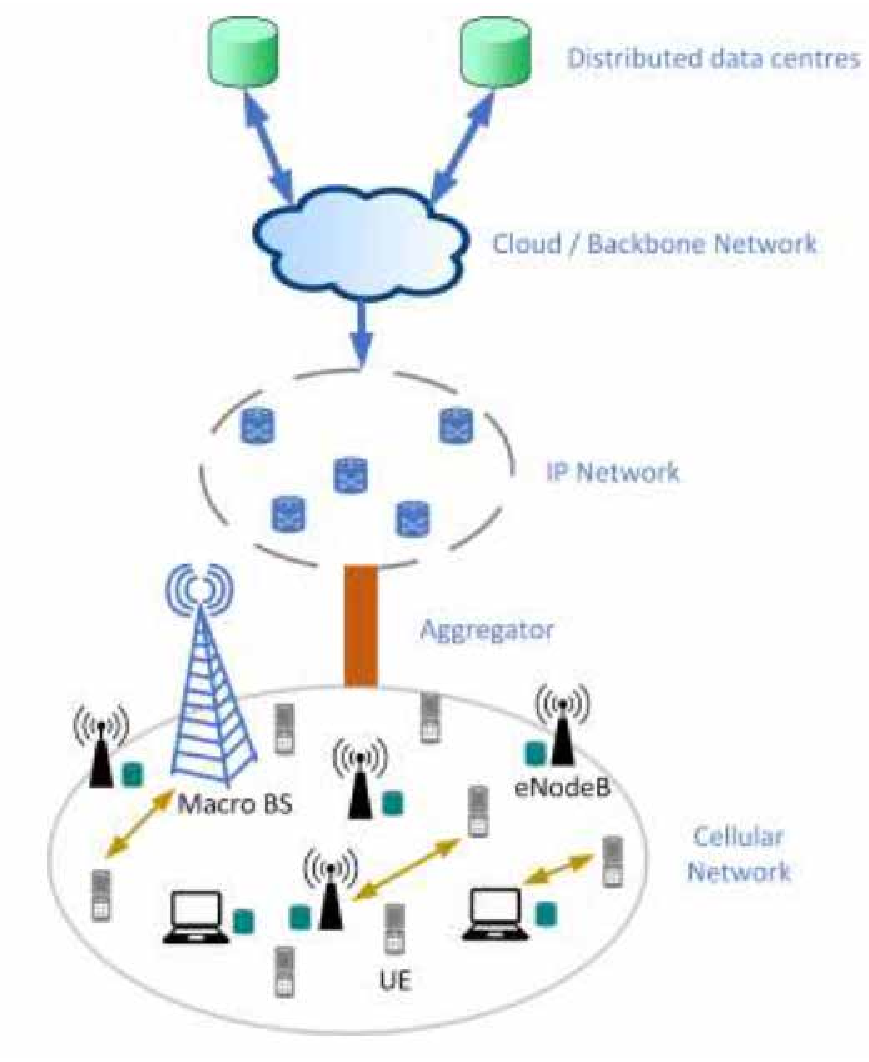

Fig. 1. Typical Network Architecture of a CCWN

If requested content is not found at the IP network, requests enter into backbone network, first in the network cloud, which typically consists of backbone mainframes or core caches in CCN terminology. Finally, if the requested content is still unavailable then the requested is forwarded to the data center (global content server) through the gateway. Basically, a CCN request traverses the distance between UE and server in search of alternative content provider, whereas traditional IP requests are directly moved towards the server.

IV. COEXISTENCE TECHNOLOGIES

In this section we discuss several possible technologies to bridge the gap between CCWN communication and traditional cellular communication. Primary problem of their coexistence is distinguishing between IP packets for traditional cellular communication and CCWN packets for cache networks, and thereafter, routing these different class of packets accordingly. So, the problem can be reduced to separation of routing plane and data plane. Separation of routing and forwarding planes also allows the incremental deployment of new data planes over the programmable compute, storage, transport infrastructure [14]. CCN can work in tandem with the software-defined network (SDN) and Network Function Virtualization (NFV) in order to achieve this multicast-driven networking framework. The deficit of inter-domain IP multicast can be resolved by this content-centric publisher/subscriber model [15]. These salient features of CCN can be integrated with IP intra-domain multicast to achieve forwarding efficiency using the shortest path routing. Existing receiver-driven TCP protocols can also be applied for CCN while generating interest packets and sending the receiver buffer capacity [16]. Relying on the receiver buffer size, CCN packets can be segmented into chunks and each chunk can be named differently [17]. Considering the humanreadable hierarchical names, the different chunk naming for the same content packet can be realized just by changing the leaf nodes' names which makes the parsing of content names for various chunks easier. After different freshness period of a particular content packet, if users ask for updated information, the custodian can send the particular chunk file which is modified rather than sending the entire packet and wasting the network bandwidth. So, a possible solution to support the routing of CCWN and IP packets is employing SDN as an overlay.

While traversing through the network, CCN packets need to be discriminated from the existing IP packets. In the protocol field of IP header, we can have one protocol option for CCN packets. Since CCN packets are also divided into interest and data packets. We can include one option for each in the Type of Service (ToS) field. This ToS field rarely used in TCP header. If the protocol file corresponds to CCN and ToS field corresponds to an interest, the edge routers can get the content name from the destination address field of the IP header and then they will perform hash mapping to get the custodian for the content. Queuing of multiple interest packets for the same content can also be resolved by the ToS field and destination field which contains the name of the content packet. The Nonce field in CCN packets to resolve the looping of the same packet can be unraveled using the TTL field in the IP header. Interest Lifetime and forwarding hints in CCN packets can be embedded inside the options field of IP header. These fields can affect the interest packet routing towards the custodian [18].

The exploitation of already available TCP-IP header format for CCN supports to attain a fair coexistence between TCP-IP and CCN traffic with modifications in the interpretation of few header fields. These modifications in interpretations can be easily resolved by programmable compute and decision making (control) plane developed with the aid of SDN over the top of CCN and traditional cellular traffic.

V. CONCLUSION

From the beginning of communication and networking, it has been a pursuit of bridging the gap between multiple technologies. Coexistence problems come into scenario whenever this heterogeneous mixture of technologies are required. In this article we discussed possible challenges for coexistence of CCWN and traditional cellular communication, due to the difference in their routing mechanisms and several other salient features of CCN. We studied how SDN can be a useful technology to overcome the routing challenge. We also discussed how switching the packet formats can solve the naming challenge and discriminating between IP packet and CCN packet. However, still there are several open research problems, such as, implementation of SDN over a cellular network, especially controlling the edge connections using SDN require a lot of infrastructure. Moreover, how additional processing delays impact the overall user experience? These are the questions that require further exploration.

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Interworking of MMWAVE and Sub-6 GHz Access Technologies for 5G Multi-Connectivity

by Kishor Chandra, Marco Mezzavilla, R. Venkatesha Prasad and Perklis Chatzimisios

The fifth generation (5G) communications technologies target diverse applications ranging from automotive, industrial communications, smart health, agriculture, entertainment, public safety and even tele-surgery. These applications have diverse requirement that includes very high data rates (in order of multi-gigabit per second), ultra- high reliability (99.99999% availability) and extremely low latency (as low as 1 ms). To fulfill these requirements, numerous new candidate technologies such as the use of millimeter wave frequency bands, licensed assisted access (LAA) in unlicensed bands, non-orthogonal multiple access (NOMA), cloud radio access (C-RAN) and massive multiple input multiple output (massive-MIMO) have emerged. It is evident that many 5G applications will be served by multiple radio access technologies in tandem to fulfill the diverse application requirements while ensuing the most efficient use of radio resources. For example, a remote-surgery application would require (i) low-latency radios to transport haptic feedback, (ii) very high data rates to transfer 360 immersive videos, and, finally, (iii) ultra-high reliable links. This aggregate set of performance targets can be met by opportunistically activating multiple radio components, at different frequency bands, to match the specific communications requirements.

Introduction

With the ratification of the 1st phase of the 3GPP's 5G New Radio (NR) standardization, it is clear that 5G air-interface would employ multiple frequency bands ranging from sub-6 GHz to mmWave frequency bands. Owing to the heterogeneous requirements of 5G applications, efficient interplay among different air-interfaces is naturally desired to exploit the full potential of available licensed and unlicensed spectrum resources. Generally, the interworking of air-interfaces can mainly be facilitated by three means: (i) Offloading, (ii) fallback, and (iii) aggregation. Offloading is the procedure of vertical handover among different radio technologies which is primarily aimed at de-congesting the licensed frequency bands. Fallback is also achieved by triggering vertical handovers, but it is generally initiated when a particular frequency band is affected by adverse channel conditions. This is particularly the case with mmWave bands when bad channel conditions arise due to blockages or beam misalignments, and the support of sub-6 GHz band is invoked to maintain the connectivity. On the other hand, aggregation aims to combine all the available frequency bands to boost the data rate by providing simultaneous multi-band connectivity. It is obvious that these operations should intelligently happen without the end user noticing any degradation in quality of service and experience.

RAT interworking in 5G and beyond networks

As a starting point for multi-radio interworking, the 1st phase of 3GPP NR provides multi-RAT dual connectivity (MR-DC). In MR-DC, a user equipment (UE) is configured to utilize radio resources provided by LTE E- UTRA (Evolved Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access) and NR access. Although the 3GPP NR provides specifications for the inter-RAT handovers between LTE and NR at the core network (CN) level, multiple possibilities for standardization remains open among 3GPP RATs and non-3GPP RATs. For example, the high data rate unlicensed access in 60 GHz band provided by IEEE 802.11ad or IEEE 802.11ay needs to be integrated with the 3GPP NR. This is needed for efficient offloading to mmWave unlicensed band, fallback to sub-6 GHz band and to facilitate the aggregation of multiple licensed and unlicensed mmWave bands.

In 4G communications similar offloading in the sub-6 GHz band is facilitated between WiFi (unlicensed) and 3G/4G access (licensed) networks using the Access Network Query protocol (ANQP) provided by 3GPP and the Access Network Discovery Function (ANDSF) provided by the Hotspot Alliance. This offloading solution works at the core-network (CN) and is referred as loose coupling solution as it is outside the operator's control. Hence it is best suited for the best effort traffic offloading to WiFi band. Since handover decisions in 4G offloading solutions are taken at the CN level, a long handover delay is expected. This delay would further increase if similar solutions would be used in case of 5G and beyond networks. The primary reason is that the mmWave band Access Point (AP) or Base Station (BS) would have a small coverage area resulting in frequent handover triggers. Furthermore, the use of mmWave beamforming would add extra delay as compared with the sub-6 GHz communication where beamforming is not mandatory.

Thus the 5G networks require new approaches for integrating licensed and unlicensed mmWave RATs with each other and with the sub-6 GHz bands. In particular, radio access network (RAN) level coupling between different air-interfaces (3GPP and non-3GPP) so that the handover process can be expedited, would be highly beneficial. In 3GPP, this technique is known as harmonization, i.e., the ability to split the connection within the CN, at a specific layer of the stack. Further, the use of directional antennas makes it difficult for mmWave BS/AP to initiate the handovers requiring new approaches at RAN layer to facilitate efficient fallback when needed. Furthermore, the differing propagation characteristics of sub-6 GHz and mmWave signals will require new solutions for efficient carrier aggregation over such a wide frequency range. We enlist the following tasks where efficient interworking solutions are required:

1. Interworking (aggregation) of licensed sub-6 GHz and mmWave frequency bands.

2. Interworking (fallback) of licensed mmWave to licensed sub-6 GHz band.

3. Interworking (fallback) of unlicensed mmWave to unlicensed sub-6 GHz band.

4. Interworking (offloading) of licensed sub-6 GHz/ mmWave to unlicensed mmWave GHz bands.

Interworking solutions are not only important to decongest the licensed bands (as it was the case with 3G/4G networks), but are also highly desired to fulfill the heterogeneity in service requirements. For example, a high data rate (multi-Gbps) application requiring low latency and ultra-high reliability would require mmWave access for high data rate, NR access for low latency and air-interface (frequency, BS, etc. diversity to ensure reliability. The conventional offloading, handovers and aggregation mechanisms would not be sufficient due to the large range of frequencies (sub-6 GHz and mmWave bands) and diversity of applications targeted by 5G and beyond networks. Specifically, the rapid fluctuation in mmWave channel conditions requires new approaches to enable fast switching among different RATs. This warrants immediate standardization efforts to establish the much needed symbiosis of multiple licensed and unlicensed RATs envisioned for 5G and beyond networks.

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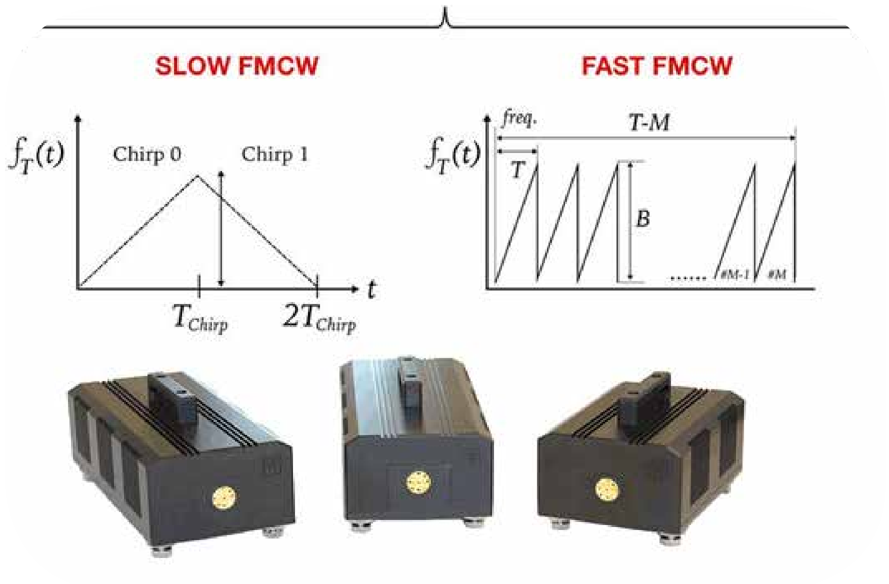
The Road Towards Faster, Simpler, and Smarter Test Equipment for MMWAVE Products

by Jeorge S. Hurtarte



The demand for millimeter wave products is quickly moving into the consumer market place. Historically, both Wi-Fi and cellular services have been operating in the crowded frequency bands under 6 GHz. Over the next few years, we expect to see new wireless communications standards widely adopted into new products (including smartphones, head-mounted displays, hot spots, etc.) that operate at mmWave frequencies over 24 GHz. [1] For example, the IEEE 802.11 working group has released two new standards, 802.11aj and 802.11ad, operating in the 40 GHz and 60 GHz unlicensed mmWave bands respectively, and is pursuing a new 802.11ay standard in the 70 GHz band. In addition, the 3GPP standards organization has recently introduced a 5G new radio (NR) [2] cellular standard capable of initially operating in the 28 GHz and 39 GHz mmWave bands as well as sub-6 GHz bands.

The GSM Association [3] has set forth five mobile industry goals for the 5G era, two of which are: “to provide boundless connectivity for all” and “to deliver future networks innovatively and with optimal economics.” Likewise, the IEEE 802 organization has set forth five criteria (5C) as conditions for communications standards development work (CSD) [4], three of which are: “broad market potential” “technical feasibility,” and “economic feasibility”. These requirements are appropriate as any new wireless standard needs to fulfill pressing customer needs while also being technically and economically viable to them.

There are, however, several new testing challenges that must be overcome in order to make mmWave products economically viable. For example, unlike sub-6 GHz products that can be tested with contacted probes, mmWave requires over-the-air testing techniques. In addition, mmWave 802.11 and 3GPP NR wireless standards specify much wider component carrier (CC) bandwidths in the range of 400 MHz to 4 GHz, as opposed to only 160 MHz for sub 6 GHz. Moreover, engineers and technicians who are experts in mmWave technology are very scarce in the market place.

In order to fulfill the technical and economic feasibility criteria of mmWave 802.11 and 3GPP NR standards, test equipment vendors must respond quickly in order to meet these new mmWave test requirements: 1) > 24 GHz frequency test coverage; 2) > 400 MHz CC bandwidth support; 3) OTA (over-the-air) test fixtures; and 4) faster, simpler, and smarter test equipment. The first three test equipment requirements relate to both the technical and economic feasibility criteria, whereas the fourth requirement pertains primarily to the economic feasibility criterion as we discuss next.

Faster, simpler, and smarter mmWave test equipment is needed for high-volume manufacturing so that the product will be economically feasible. Faster test equipment minimizes the required set-up time, calibration time, and unit test time throughput, all of which have a direct impact on the cost of test (COT), which in turn affect the product unit cost. Simpler test equipment makes it easy to use and is “plug-and-play” for the vast majority of users in the manufacturing environment who are not mmWave experts, and also accelerates the time-to-market of mmWave consumer products. Smarter test equipment simplifies dealing with the new mmWave test challenges for a larger group of R&D developers. Smarter test equipment also has embedded software that optimizes the units per hour (UPH) throughput time, speeds up the troubleshooting time of failed units, and makes the test equipment accessible to a wider group of R&D and software developers.

Whereas most bench rack-and-stack mmWave test equipment available in today’s ecosystem fulfills the frequency, bandwidth and OTA test requirements of the new 802.11aj/ad/ay and 5G 3GPP NR standards in the R&D lab, there is still work to be done in the test industry as mmWave products enter the high-volume manufacturing line. Fortunately, leading test equipment companies are starting to introduce mmWave test equipment that is faster, simpler, and smarter for the manufacturing environment, thereby paving the way to fulfilling the economic feasibility criterion of the both the GSM Association and IEEE 802 CSD 5Cs.

Dr. Jeorge S. Hurtarte is currently RF Market Segment Manager at LitePoint Corporation in Sunnyvale, CA, USA. Prior to joining LitePoint, Dr. Hurtarte held various technical and management positions at Teradyne, TranSwitch, and Rockwell Semiconductors. He holds Ph.D. and B.S. degrees in electrical engineering, an M.S. in telecommunications, and an M.B.A. Dr. Hurtarte has served on the Advisory Board of Directors of the Global Semiconductor Alliance, TUV Rheinland of North America, and the NSF’s Wireless Internet Center for Advanced RF Technology. He is the secretary of the IEEE 802.11ay task group. He is also the lead co-author of the book Understanding Fabless IC Technology.
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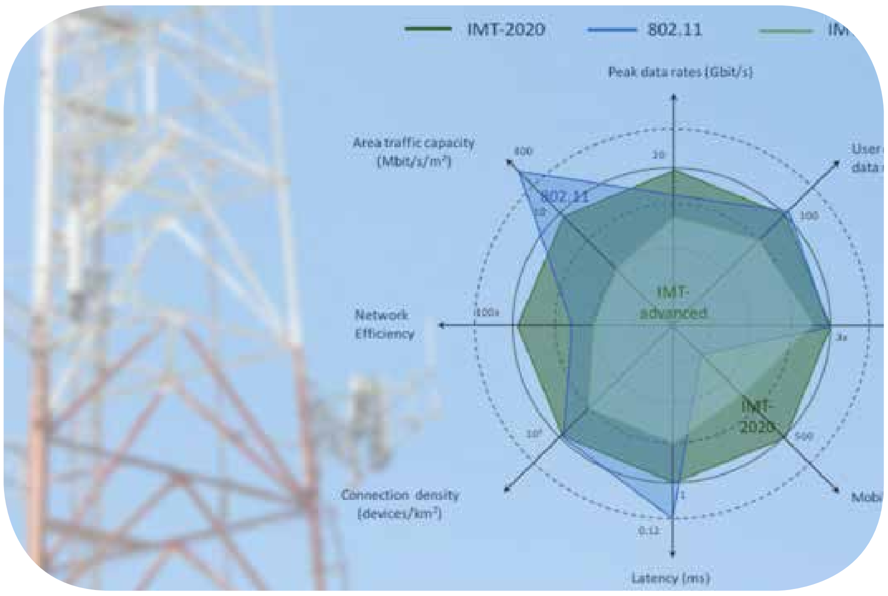
1. The radio frequency (RF) spectrum above 24 GHz is usually referred to as the mmWave spectrum due to the very short wavelengths as compared to RF spectrum in the sub-6 GHz range.
2. See http://www.3gpp.org/news-events/3gpp-news/1929-nsa_nr_5g
3. E. Obiodu and M. Giles, “The 5G era: Age of boundless connectivity and intelligent automation,” GSMA, Feb. 27, 2017. [Online]. Available: https://www.gsmaintelligence.com/research/2017/02/the-5g-era-age-of-boundless-connectivity-and-intelligent-automation/614/
4. See https://mentor.ieee.org/802.11/dcn/14/11-14-1152-08-ng60-ng60-proposed-csd.docx

How well-positioned is IEEE 802.11ax to meet the IMT-2020 performance requirements?

by Rakesh Taori and Farooq Khan



The industry is buzzing with activities related to the next generation of wireless communications technology—5G! In parallel, the telecoms industry as a whole—service providers, vendors, academia, and standards-setting bodies—are working under the umbrella of IMT-2020 to define exactly what 5G will be. The term "IMT-2020" was coined in 2012 by the International Telecommunication Union Radiocommunication Sector (the ITU-R) and refers to an international mobile telecommunication system with a target date set for 2020. The ITU-R Study Groups develop global standards (recommendations) and the technical bases for decisions taken at the World Radio Congress (WRC). Relevant to our discussion here is Working Party 5D (WP5D), which operates under Study Group 5 (SG5) of the ITU-R. WP5D is responsible for the overall radio system aspects of international mobile telecommunications (IMT) systems, comprising the IMT-2000, IMT-Advanced, and IMT for 2020 and beyond.

Today's 3G and 4G mobile broadband systems are based on the ITU's IMT standards. The worldwide 3G deployments that commenced around the year 2000 were based on IMT-2000 specifications, and 4G wireless cellular technology, now being progressively deployed worldwide, is based on IMT-Advanced standards.

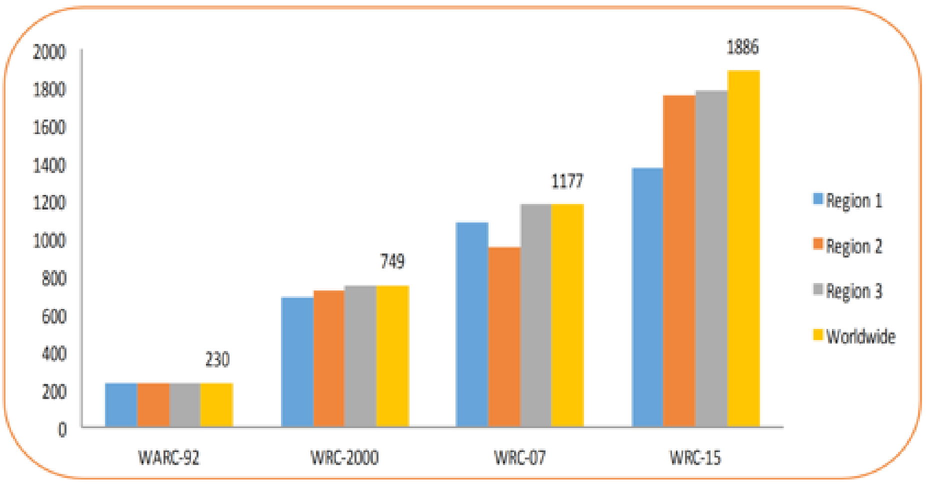
Of great interest to the telecommunications community is the amount of spectrum identified for IMT (Fig. 1), which can be used for IMT systems. About 27.5 GHz of new spectrum in the millimeter wave bands is under study for the World Radio Congress WRC 19, to be identified for IMT!

In early 2012, the ITU-R embarked on a program to develop "IMT for 2020 and beyond," setting the stage for 5G research activities around the world. The ITU-R document M.2083 defines the framework and overall objectives of IMT for 2020 and beyond. By the end of 2017, the WP 5D had already completed the documents required for driving the selection and standardization of technologies for IMT-2020 and beyond:

- "Minimum requirements related to technical performance for IMT-2020 radio interface(s)" (5/40)
- "Guidelines for evaluation of radio interface technologies for IMT-2020" (5/57)
- "Requirements, evaluation criteria, and submission templates for development of IMT-2020" (5/56)
- "Submission, evaluation process and consensus building for IMT-2020" (Doc. IMT-2020/2(Rev.1))

In 2018–2020, evaluation by independent external evaluation groups and definition of the new radio interfaces to be included in IMT-2020 will take place. The entire process is planned to be completed in 2020, when a draft of new ITU-R recommendations with detailed specifications for the new radio interfaces will be submitted for approval within the ITU-R.

Total amount of spectrum (MHz) identified for IMT



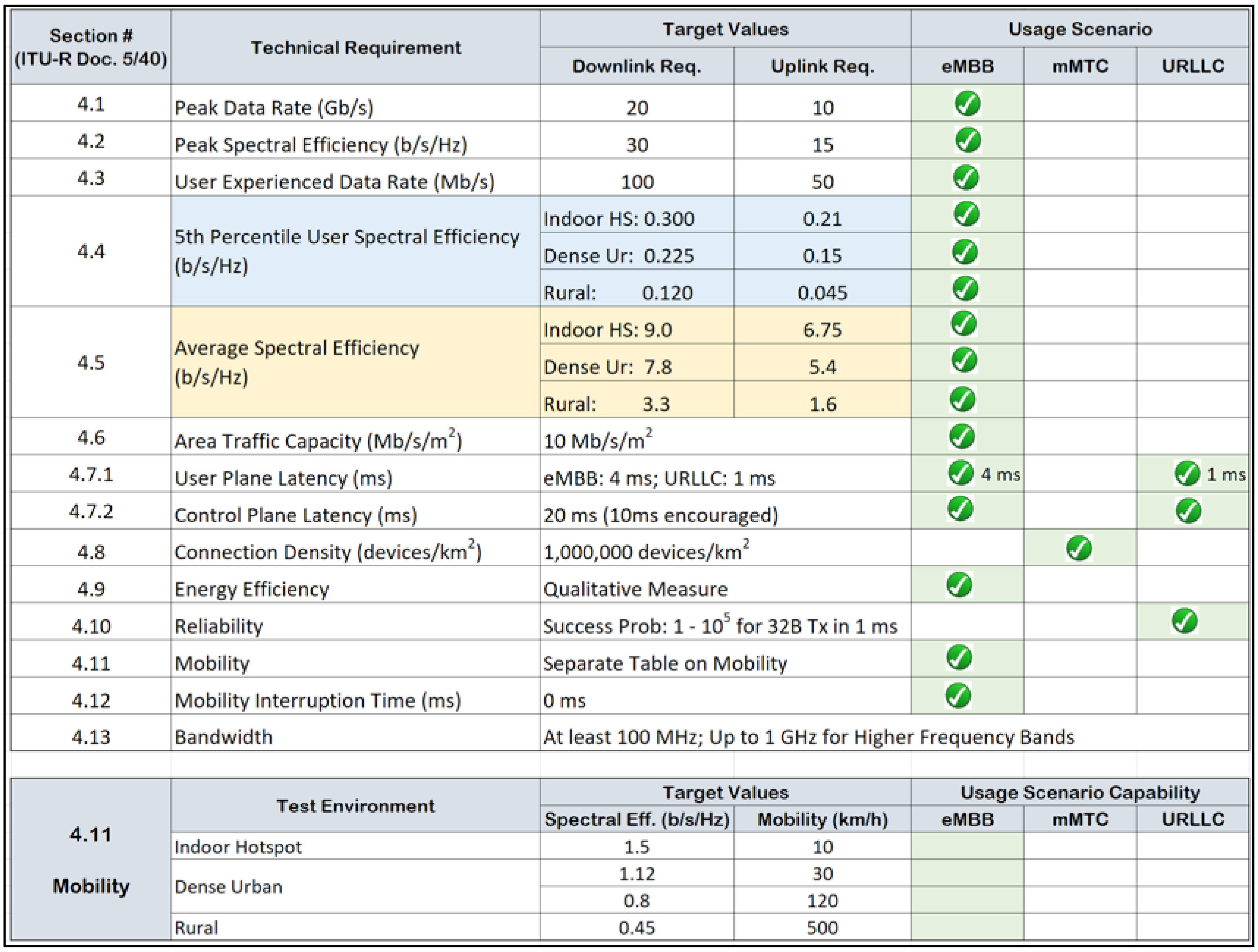
New Spectrum: Bands under Study for WRC-19

Existing Mobile Allocation	No Global Mobile Allocation
24.25 GHz – 27.5 GHz	31.8 – 33.4 GHz
37 – 40.5 GHz	40.5 – 42.5 GHz
42.5 – 43.5 GHz	
45.5 – 47 GHz	
47.2 – 50.2 GHz	47 – 47.2 GHz
50.4 – 52.6 GHz	
66 – 76 GHz	
81 – 86 GHz	

Fig. 1. 1886 MHz has been identified for IMT; 27.5 GHz is under study for WRC-19.

The three categories of usage scenarios identified for IMT-2020 are:

1. Enhanced mobile broadband (eMBB) to support new user experiences such as those enabled by augmented reality/virtual reality (AR/VR).
2. Massive machine-type communications (mMTC) to support machine-to-machine (M2M) services with massive numbers of end devices.
3. Ultra-reliable and low latency communications (URLLC) to support unprecedented levels of reliability, availability, and quality of service, with very low latency. The minimum performance requirements for systems to qualify as IMT-2020 systems are summarized in Table 1 and Table 2.



Section # (ITU-R Doc. 5/40)	Technical Requirement	Target Values		Usage Scenario		
		Downlink Req.	Uplink Req.	eMBB	mMTC	URLLC
4.1	Peak Data Rate (Gb/s)	20	10	✓		
4.2	Peak Spectral Efficiency (b/s/Hz)	30	15	✓		
4.3	User Experienced Data Rate (Mb/s)	100	50	✓		
4.4	5th Percentile User Spectral Efficiency (b/s/Hz)	Indoor HS: 0.300	0.21	✓		
		Dense Ur: 0.225	0.15	✓		
		Rural: 0.120	0.045	✓		
4.5	Average Spectral Efficiency (b/s/Hz)	Indoor HS: 9.0	6.75	✓		
		Dense Ur: 7.8	5.4	✓		
		Rural: 3.3	1.6	✓		
4.6	Area Traffic Capacity (Mb/s/m^2)	10 Mb/s/m^2		✓		
4.7.1	User Plane Latency (ms)	eMBB: 4 ms; URLLC: 1 ms		✓ 4 ms		✓ 1 ms
4.7.2	Control Plane Latency (ms)	20 ms (10ms encouraged)		✓		✓
4.8	Connection Density (devices/km^2)	1,000,000 devices/km^2			✓	
4.9	Energy Efficiency	Qualitative Measure		✓		
4.10	Reliability	Success Prob: 1 - 10^5 for 32B Tx in 1 ms				✓
4.11	Mobility	Separate Table on Mobility		✓		
4.12	Mobility Interruption Time (ms)	0 ms		✓		
4.13	Bandwidth	At least 100 MHz; Up to 1 GHz for Higher Frequency Bands				

4.11 Mobility	Test Environment	Target Values		Usage Scenario Capability		
		Spectral Eff. (b/s/Hz)	Mobility (km/h)	eMBB	mMTC	URLLC
	Indoor Hotspot	1.5	10			
	Dense Urban	1.12	30			
		0.8	120			
	Rural	0.45	500			

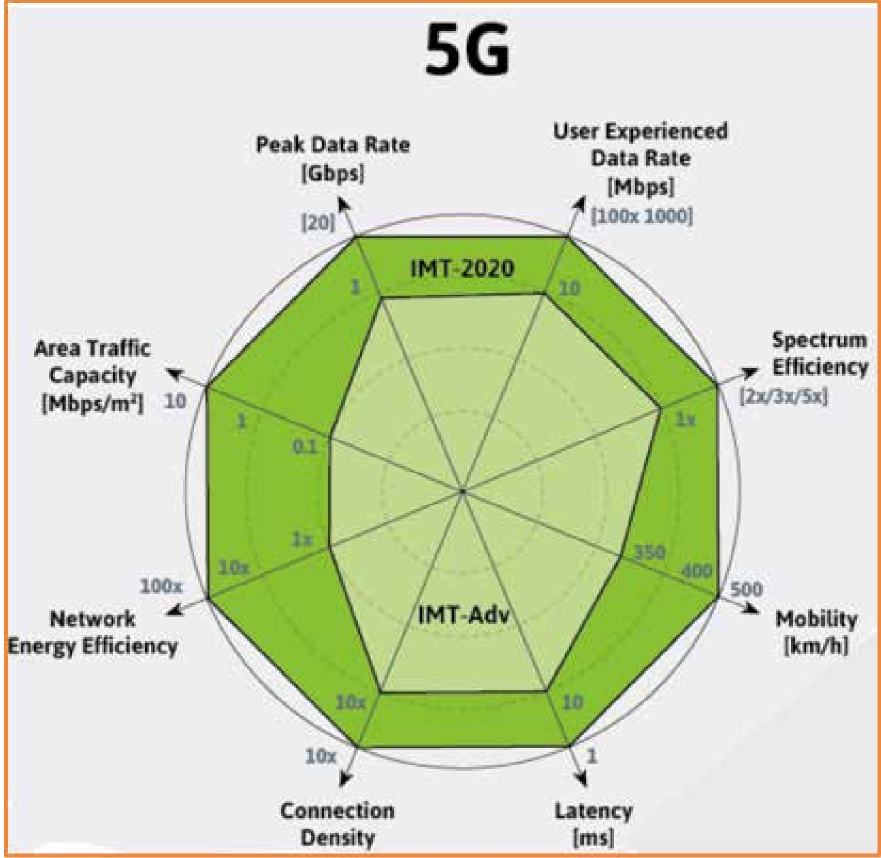
Mobility requirements for the eMBB usage scenario are summarized in Table 2.study for WRC-19.

Table 2. eMBB Mobility Requirements

4.11 Mobility	Test Environment	Target Values	
		Spectral Eff. (b/s/Hz)	Mobility (km/h)
	Indoor Hotspot	1.5	10
	Dense Urban	1.12	30
		0.8	120
	Rural	0.45	500

The spider charts illustrated in Fig. 2 compare the performance requirements for IMT-Advanced and IMT-2020.

Fig. 2. Comparison of performance requirements between IMT-Advanced ("4G") and IMT-2020 ("5G").



IMT-2020 (5G) is expected to be very different from its predecessors [IMT-2000 (3G) and IMT-Advanced (4G)] in that it is very likely to be a far broader platform, encompassing multiple radio access technologies (RATs), integrating with wireline connections, and supported by new network architectures built on virtualization and software-defined networking (SDN). More specifically, IMT-2020 specifications will:

- include high-frequency millimeter wave bands (e.g., 28 GHz, 39 GHz, and 60 GHz) (Table in Fig. 1);
- span licensed and unlicensed spectrum, aggregating both types together, and will also harness emerging models for spectrum sharing;
- in addition to enhanced mobile broadband (eMBB), support M2M (machine-to-machine) and IoT (Internet of Things) services that have already impacted the IMT-2020 requirements (Table 1); and
- require a whole new architecture that goes well beyond the radio and packet core to enable virtual "slices" of capacity to be assigned and optimized for specific users on-demand.

802.11 technologies (which form the basis of Wi-Fi) have been continuously evolving, bringing 5G capabilities to non-spectrum owners such as cable operators, city authorities, or private network providers. See Table 3 for a summary of the evolution of the IEEE 802.11 standard.

Table 3. Evolution of the IEEE 802.11 Standard

	802.11 (Legacy)	802.11b (Legacy)	802.11a (Legacy)	802.11g (Legacy)	802.11n (HT)	802.11ac (VHT)	802.11ax (HE)
Year Ratified	1997	1999	1999	2003	2009	2014	2019 (Expected)
Operating Band	2.4 GHz/IR	2.4 GHz	5 GHz	2.4 GHz	2.4/5 GHz	5 GHz	2.4/5 GHz
Channel BW	20 MHz	20 MHz	20 MHz	20 MHz	20/40 MHz	20/40/80/160 MHz	20/40/80/160 MHz
Peak PHY Rate	2 Mbps	11 Mbps	54 Mbps	54 Mbps	600 Mbps	6.8 Gbps	10 Gbps
Link Spectral Efficiency	0.1 bps/Hz	0.55 bps/Hz	2.7 bps/Hz	2.7 bps/Hz	15 bps/Hz	42.5 bps/Hz	62.5 bps/Hz
Max # SU Streams	1	1	1	1	4	8	8
Max # MU Streams	NA	NA	NA	NA	NA	4 (DL only)	8 (UL & DL)
Modulation	DSSS, FHSS	DSSS, CCK	OFDM	OFDM	OFDM	OFDM	OFDM, OFDMA
Max Constellation / Code Rate	DQPSK	CCK	64-QAM, 3/4	64-QAM, 3/4	64-QAM, 5/6	256-QAM, 5/6	1024-QAM, 5/6
Max # OFDM tones	NA	NA	64	64	128	512	2048
Subcarrier Spacing	NA	NA	312.5 kHz	312.5 kHz	312.5 kHz	312.5 kHz	78.125 kHz

The latest IEEE 802.11 standard, 802.11ax, currently under development and seen as the first "5G" 802.11 release, is expected to be finalized in 2018. The latest commercially available Wi-Fi standard based on 802.11ac already supports multi-gigabit data rates. 802.11ax is targeted at delivering gigabit data rates in dense environments. The first pre-standard 802.11ax chipsets from various vendors have already been announced.

Table 4. IEEE 802.11ac Waveforms Compared With Other 5G Candidate Waveforms

Parameter	**802.11ac**	**802.11ax**	**Verizon 5G TF**	**3GPP 5G-NR**
Basic Waveform (DL/UL)	OFDM	OFDM	OFDM	OFDM
Subcarrier Spacing (kHz)	312.5	78.125	75	15, 30, 60, **120** and 240
OFDM Symbol duration (μs)	3.2	12.8	13.33	8.33
Cyclic Prefix Length (μs)	0.4 and 0.8	0.8, 1.6, and 3.2	1.04 and 0.9375	1.107 and 0.586
Bandwidth support (MHz)	n x (20, 40, 80, 160)	n x (20, 40, 80, 160)	n x 100 MHz	n x 100 MHz
FFT size	64, …, 512	64, …, 2048	Up to 2048	Up to 4096
Coding	BCC/LDPC	BCC/LDPC	LDPC	Data: LDPC; Control: Polar
Modulation order (max)	256 QAM	1024 QAM	64 QAM	256 QAM
Number of Spatial Streams	Up to 8	Up to 8	Up to 8	Up to 8
MIMO Support	Single & Multi user	Single & Multi user	Single & Multi user	Single & Multi user
MIMO/Beamforming Feedback	Explicit	Explicit	CQI, Channel Rec.	CSI, CQI, PMI, etc.

The IEEE 802.11ac and ax waveforms fare quite well when compared with 3GPP's New Radio (NR), which is being submitted as a candidate technology for IMT-2020. Table 4 summarizes the numerology for IEEE 802.11ac, 802.11ax, Verizon 5G TF (a proprietary standard from Verizon Wireless for pre-5G deployments), and 3GPP NR systems. The suitability of the IEEE 802.11ax standard to meet the IMT-2020 requirements for hotspot environments has been studied in detail and summarized in Table 5.

Table 5. 802.11ax capabilities and IMT-2020 Requirements

Parameter	Desired Range	Use Case	802.11ax capability
Peak data rate	DL/UL: 20/10 Gbps	eMBB	19.2 Gbps DL/UL (8x8 HE160)
Peak spectral efficiency	DL/UL: 30/15 bits/s/Hz	eMBB	60 bits/s/Hz (8x8)
5%ile user spectral efficiency	DL/UL: 0.3/0.21 bits/s/Hz DL/UL: 0.225/0.15 bits/s/Hz	eMBB: Indoor Hotspot eMBB: Dense Urban	Expected to Meet
5%ile user experienced data rate	DL/UL: 100/50 Mbps	eMBB	Expected to Meet
Avg Spectral efficiency	DL/UL: 9/6.75 bits/s/Hz/TRxP DL/UL: 7.8/5.4 bits/s/Hz/TRxP	eMBB: Indoor Hotspot eMBB: Dense Urban	Expected to Meet
Area traffic capacity	10 Mbps/m^2	eMBB: Indoor Hotspot eMBB: Dense Urban	Expected to Meet
User Plane Latency	4 ms 1 ms	eMBB URLLC	Can meet
Control Plane Latency	20 ms (Encourage 10 ms)	eMBB/URLLC	Can meet for STA initiated
Connection density	10^6 connected devices/km^2	mMTC	Not in focus for eMBB
Energy efficiency	Efficient data transmission in high loads Low energy consumption in absence of data High sleep ratio and long sleep duration	eMBB	Can meet
Reliability	1-10^{-5} success probability for transmitting a Layer 2 PDU within 1ms at coverage edge for Urban Macro-URLLC	URLLC	Not in focus for eMBB
Mobility (defined only for UL)	1.5 bit/s/Hz UL @ 10 kph 1.12 bit/s/Hz UL @ 30 kph	eMBB: Indoor Hotspot eMBB: Dense Urban	Can meet
Mobility Interruption Time	0 ms	eMBB and URLLC	~ 2-3 ms
Bandwidth	Scalable: Min 100 MHz, up to 1 GHz		160 MHz

A comprehensive analysis of the suitability of the IEEE 802.11 standard to meet the IMT-2020 requirements has been documented by the Wireless Broadband Alliance in their annual industry report. Fig. 3 summarizes a key conclusion of this report, which show that the 802.11 technologies can meet and exceed the IMT-2020 requirements related to area traffic capacity and latency, but are likely to fall short in meeting the mobility requirements for very high vehicular speeds (500 km/hr). 802.11ax has focused on meeting the capacity requirement.

With each technology having its own strengths and weaknesses, it is important that operators can use and have the choice to use both 802.11 and 3GPP as well as other technologies to achieve the best overall performance in accordance with their needs.

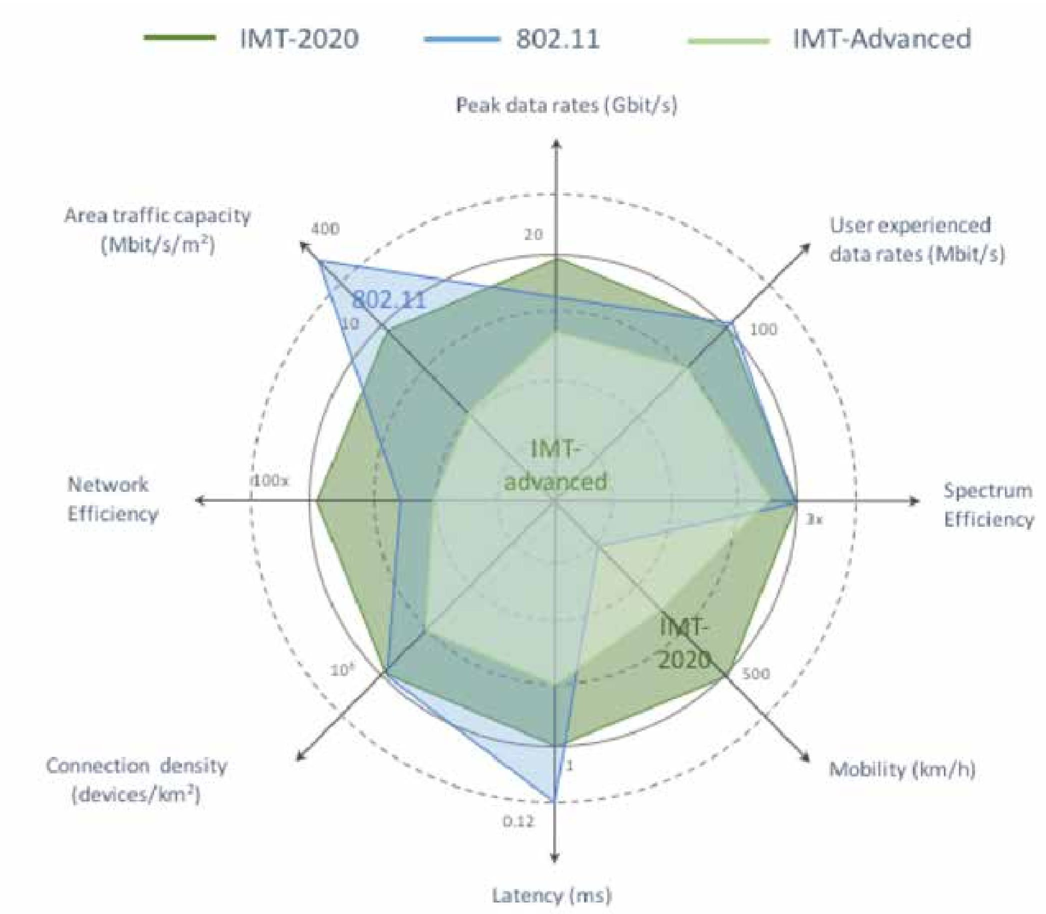
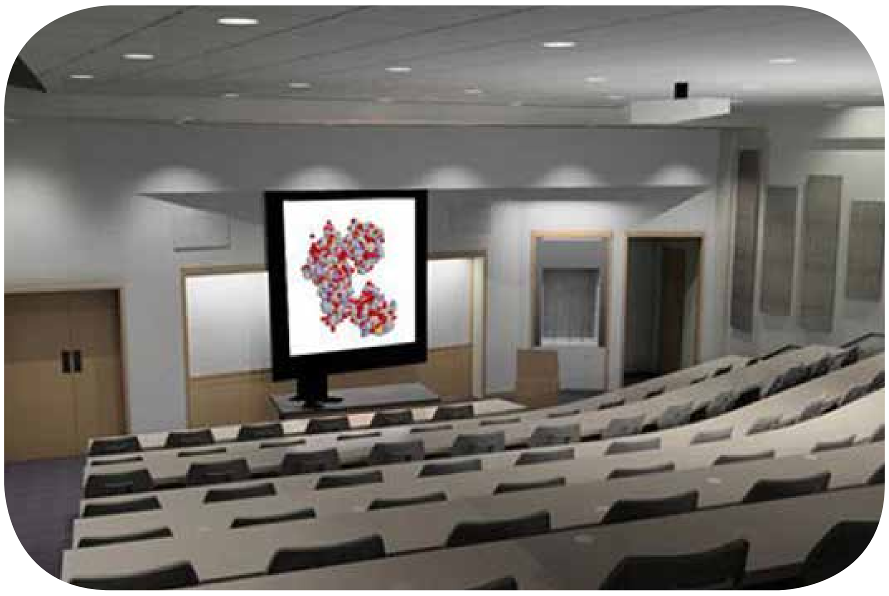


Fig. 3: 802.11 capabilities compared with those of IMT-Advanced and IMT-2020.

Rakesh Taori and Farooq Khan
Phazr Inc., Allen, TX

My efforts to teach standards in the undergraduate and graduate programs at the University of Hartford

by Hemchandra M. Shertukde, Ph.D. P.E.



I have been a member of IEEE since 1984, when I started as a graduate student pursuing my doctorate at the University of Connecticut (UCONN) in Storrs. Prior to coming to graduate studies in controls and systems engineering, I had considerable experience in the industry, having worked for Tata Motors and Crompton Greaves Limited in India. These two stints lasted for eight years starting from 1975 after I graduated with a B.Tech (Honors) with distinction from the Indian Institute of Technology in Kharagpur, India. Tata Motors (erstwhile TELCO) had collaborated with Daimler-Benz in Germany, and Crompton Greaves Limited with Westinghouse in the United States/Canada. I was very proficiently trained in the best design and manufacturing practices at both locations.

In 1984, my introduction to graduate work was mostly theoretical. I still remember the words of my first academic adviser at UCONN, who said to me, "Welcome to high tech from a low-tech industry." These words still ring in my years today. Little did my first adviser know how high tech the industry was in relation to automobiles and transformers. I decided then that for anyone to be a successful engineer, one has to be conversant with standards, which govern the best practices of design, manufacturing, and use of a device in a particular application. I learned through several technical committees attached to the IEEE-Standards Association that IEEE was a great source for standards work. Fortunately, in 1996, I found one suitable for my research and teaching in the area of transformer design, manufacturing, and usage in the form of the IEEE Transformer Committee as a part of IEEE-PES.

I had a great opportunity to fulfill my dream of teaching students several applications and also instilling in them the concept of inculcating best practices with guidance from suitable standards. I have taught most of the courses in electrical power engineering and controls since I started my academic career at UHART in 1988 and during the five years prior to this at UCONN. I encouraged my students to become IEEE student members in return for 10% points towards their final grade and pursuit of a tangible project. Students in my courses could not avoid this bait, but the net result was an increased interest in the course material as well as the related additional information they obtained from IEEE Spectrum Magazine.

So far, I have had a hand in graduating close to 5,000 students over the last 30 years. I hope this small step in helping students become interested in standards goes a long way in producing successful electrical engineers for posterity's sake so that "the light remains on" forever!

Hemchandra M. Shertukde, Ph.D. P.E. Hemchandra obtained his Bachelor of Technology (B.Tech – Honors) with high distinction from Indian Institute of Technology, Kharagpur in 1975 in Controls and Power. He graduated from the University of Connecticut obtaining his Master of Science in Electrical Engineering in 1985 and PhD in 1989 in Electrical and Systems Engineering with focus on passive target tracking. He was the chair of the ECE Department at the University of Hartford from 1994-1998 and director of graduate studies from 1983 to 1988, laying a foundation for the graduate program at the university.

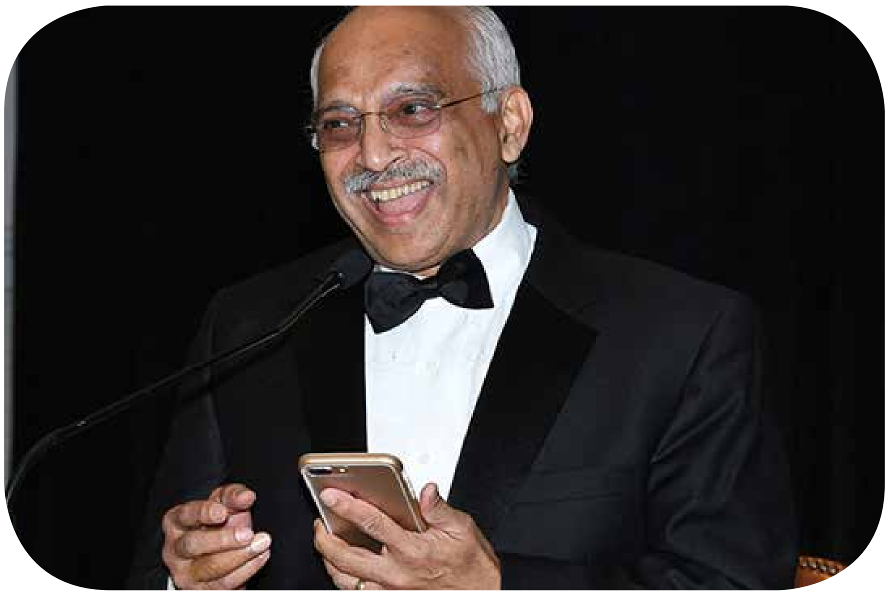
IEEE-EAB/IEEE-SA Standards Education Award

by IEEE SA

For effectively integrating power systems and transformer standards into academic and professional development programs, and for his active encouragement of IEEE student membership

Over the past 29 years, Hemchandra Shertukde has been teaching courses in electrical engineering at the University of Hartford encompassing machines, power system analysis, transformer theory and design, control systems, and signal processing. He is a tenured professor and joined the faculty in the Electrical and Computer Engineering (ECE) Department in the fall of 1988.

Hemchandra obtained his Bachelor of Technology (B.Tech – Honors) with high distinction from Indian Institute of Technology, Kharagpur in 1975 in Controls and Power. He graduated from the University of Connecticut obtaining his Master of Science in Electrical Engineering in 1985 and PhD in 1989 in Electrical and Systems Engineering with focus on passive target tracking. He was the chair of the ECE Department at the University of Hartford from 1994-1998 and director of graduate studies from 1983 to 1988, laying a foundation for the graduate program at the university.



Hemchandra's stint in publishing started four years ago with Taylor and Francis Company (CRC Press). Since then, Hemchandra has published a book on distributed photovoltaic (DPV) grid transformers and a book on digital controls with CRC Press. The latter has been adopted by California State University for their graduate courses and the former will be translated into Chinese by the first quarter of 2017. In 2016 he published a solo book, Random Signals and Noise for Engineers, with Sentia Publishing, Texas, USA. Earlier he published two books with Verlag-Dr. Mueller on transformers and target tracking. He presently holds two commercialized patents and has published over 75 journal/proceedings articles in reputed IEEE journals, transactions, and conferences. Hemchandra is a member of ETA Kapa Nu and Tau Beta Pi Honor Societies. He is also a senior member of the American Institute of Aeronautics and Astronautics (AIAA) and SPIE, the international society for optics and photonics.

Recently, Hemchandra received the 2017 Outstanding Engineer Award from the IEEE-CT Chapter. In 2017 he was also nominated to be elevated to the rank of Fellow of IEEE.

Please read Hemchandra Shertukde's article in this issue of the IEEE Standards Education E-Magazine, "My Efforts to Teach Standards in the Undergraduate and Graduate Programs at the University of Hartford."

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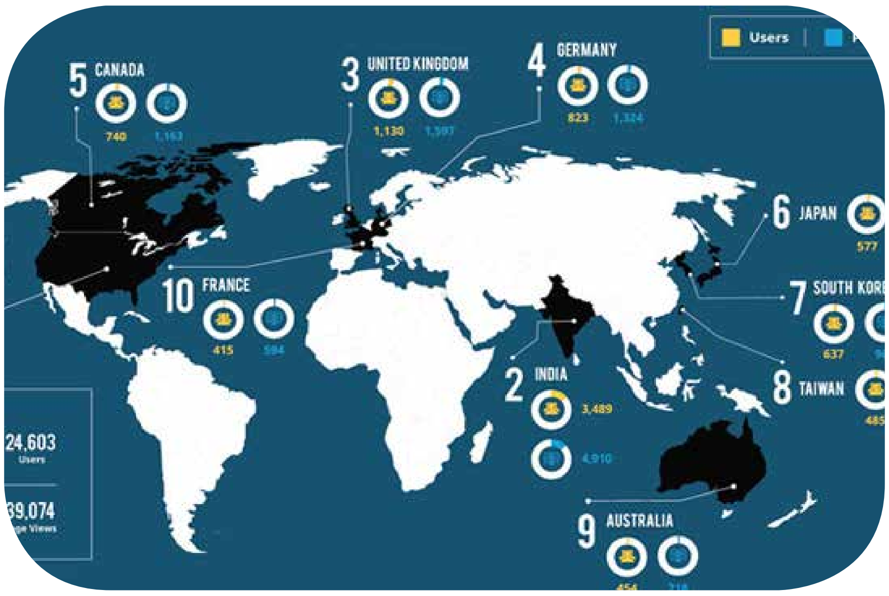

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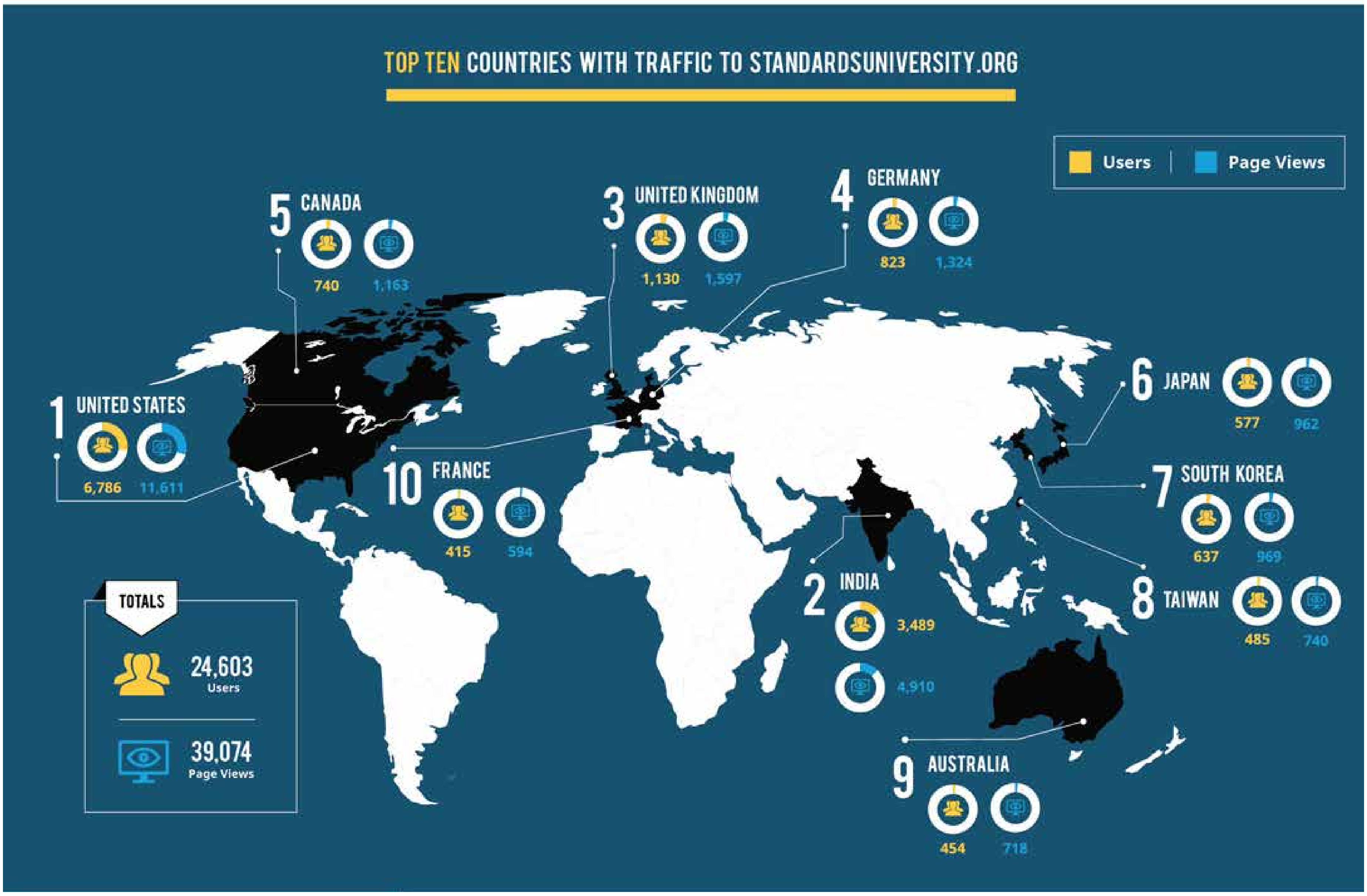

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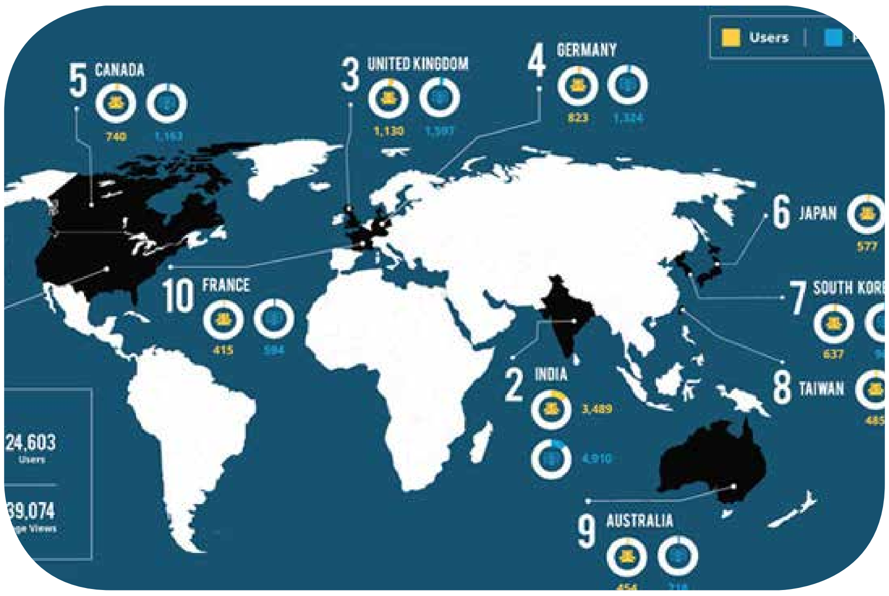

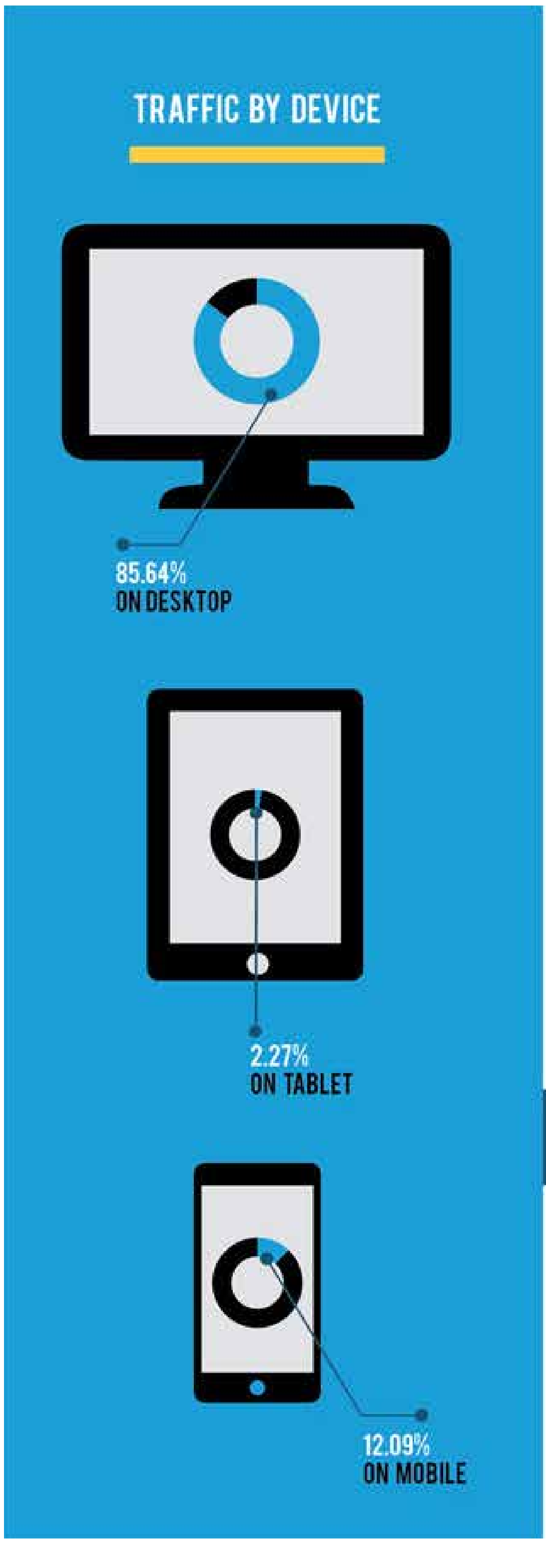

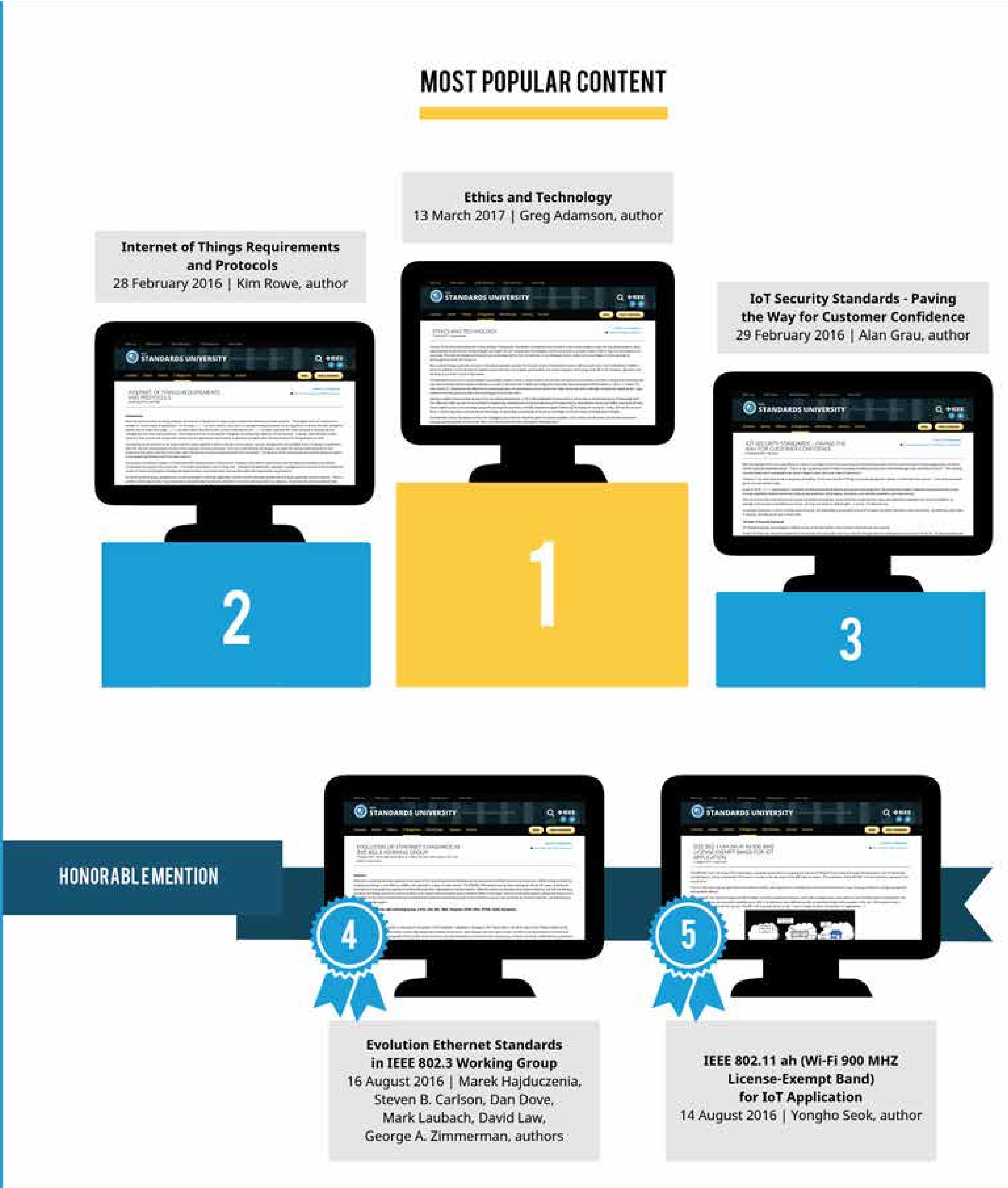

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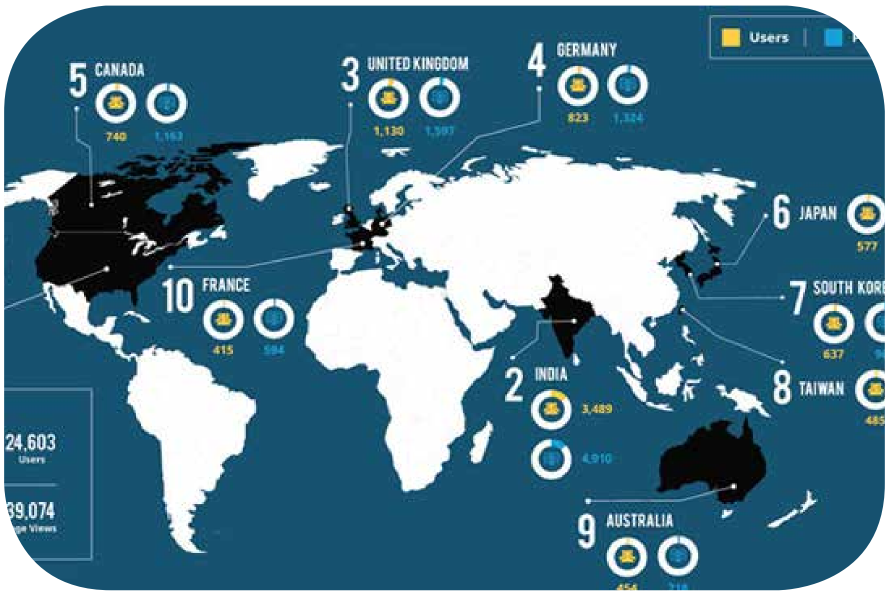

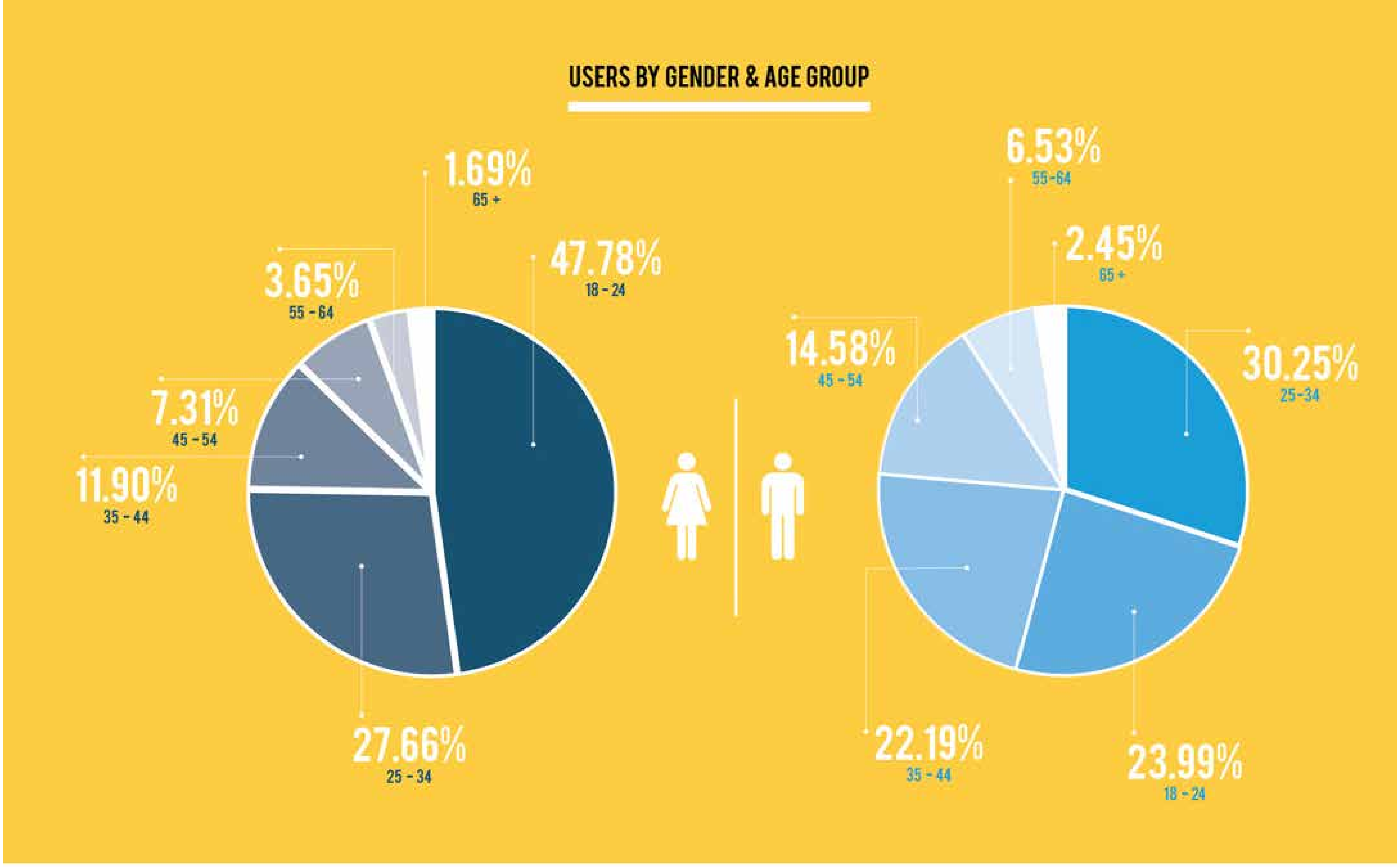

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Best of Student Application Papers

by Roman Baraniuk, Tetiana Ryzhakova,
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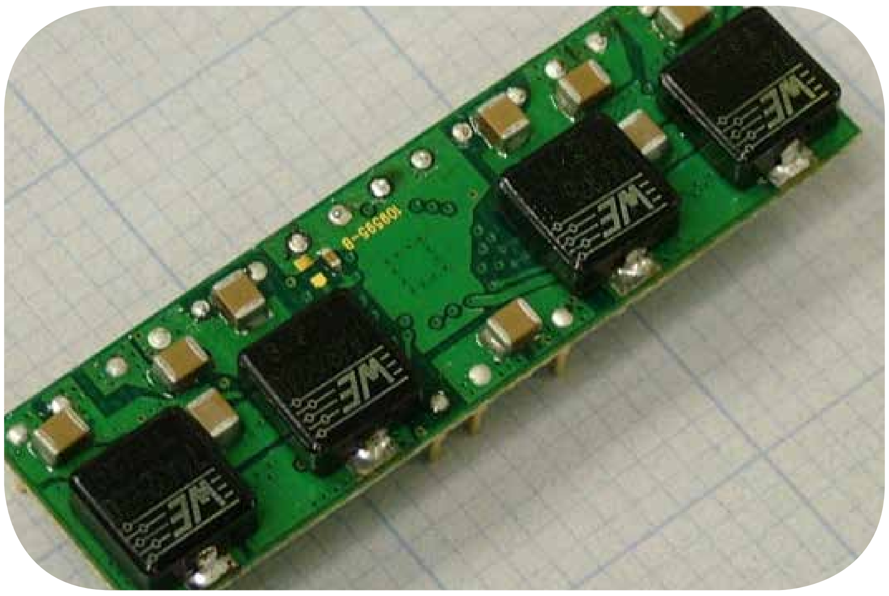

Thermal and Surge Current Protection Means for Semiconductor Non-Isoloted Power Converters

Abstract—The combined calculation of electromagnetic and thermal processes in semiconductor non-isolated power converters and the analysis of semiconductor switch junction overheating were carried out to develop thermal and surge current protection means, which are based on soft start system control depending on semiconductor switch junction temperature and normalization of the inductor parameters depending on converter temperature changing.

I. Introduction

A relevant issue for designing semiconductor power converters is development of thermal and surge current protection means for normal operation and transient modes. Nearly 60% of failures are temperature or surge current induced [1]. Heating of inductors, capacitors and transformers leads to transient changes, which cause surge current value increase in the circuits of the converters. These deviations are undesirable and dangerous for semiconductor devices during device restart, load drop or short circuit.

II. Goal Statement

The prototype converter considered in this study includes a half-bridge inverter with a soft start system, loaded with an output bridge inverter with control system (voltage feedback). Despite of using the soft start, there is a danger that surge currents will lead to device breakdown. Fig. 1 represents transistor current curves deviations, caused by the components heating, during device restart and load drop. Fig. 1 a shows surge current of half-bridge inverter transistors during restarting the heated device. Fig. 1 b shows surge current of bridge inverter transistors during load drop. Both modes are unsafe for semiconductor devices and require special solutions, which combine protection from surge current and thermal processes.

The aim of this work is to create surge and thermal protection means for semiconductor devices of DC-DC non-isolated converters, using thermal changes of magnetizing inductance for transient current chopping and through restart of adaptive soft start system after load drop or short circuit, and considering actual surge protective and inductive elements standards.

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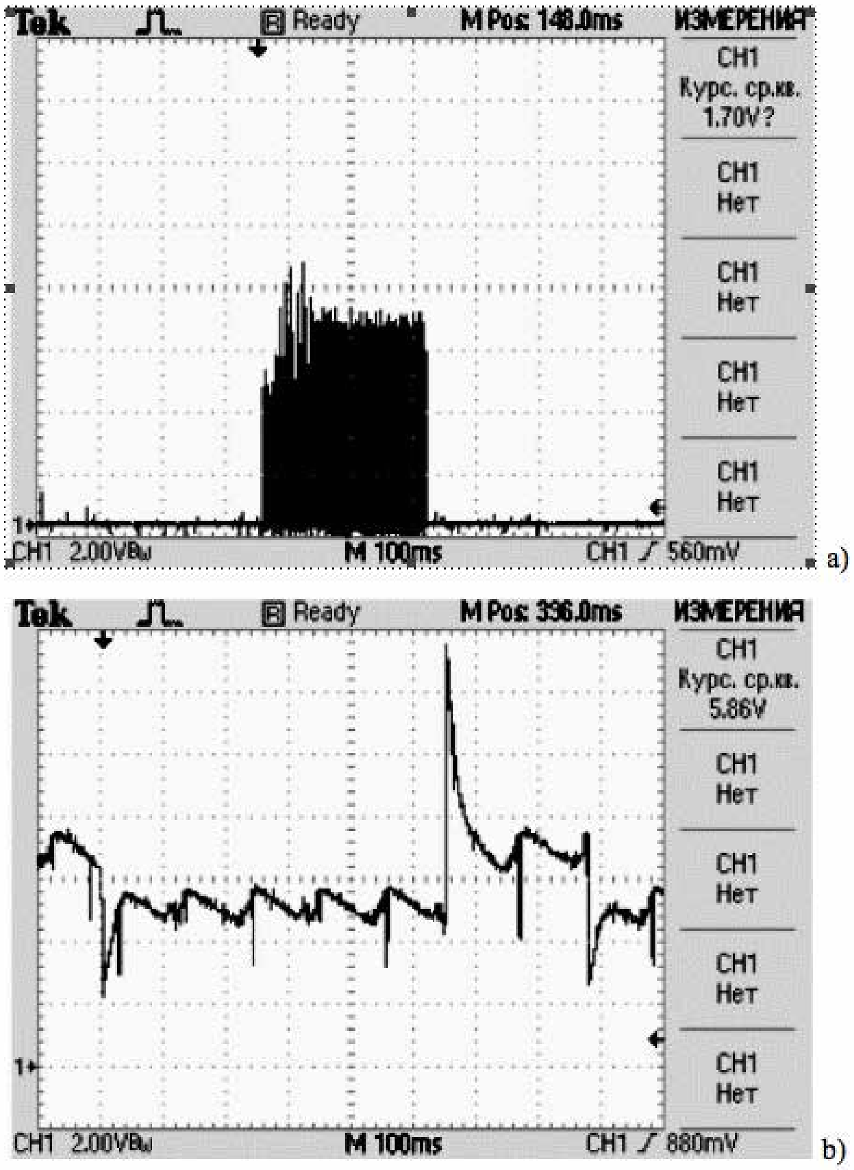


Fig. 1. Transistor current curves deviations, caused by the components heating: a) surge current of half-bridge inverter transistors during restarting the heated device; b) surge current of bridge inverter transistors during load drop

The use of suggested surge and thermal protection means should increase productivity and lifetime of semiconductor converters operating in pulse mode, reduce maintenance expenses and number of failures caused by the breakdown of power semiconductor elements and elements of filter.

III. Using the Standards

To calculate and test the temperature derating and the temperature coefficient of breakdown voltage, the standard C62.35-2010 [2] will be used. According to the standard, the analysis, the calculation and the testing of components will be carried out under normal conditions (normal operating range: −5°C to +55°C, extended operating range: −40°C to +85°C; the components were applied in the systems where the frequency is between zero (DC) and several GHz, depending on the component's capacitance and leakage current; the component surge ratings exceeds the expected amplitude, wave shape and occurrence rate of surges in the system application over the expected system ambient temperature range; the component electrical ratings and characteristics, after temperature derating for the expected ambient temperature range of the system, meet the system needs). In the operation points of the breaking normal conditions, new component builds, or additional protection solutions were built. Untypical conditions, which will be tested, are the following: temperature values that exceed the normal service conditions; abnormally high system surge currents whereby the rating of the device is exceeded; the maximum transient repetition rate of specified waveform that normally occurs in the system can't be safe for heated devices (during junction temperature rise, maximal safe current for junction goes down).

According to the standard C62.35-2010, the following failure mode tests will be applied: degradation failure mode test, where the components have a stand-by current greater than the specified value; short-circuit failure mode test; open circuit failure mode test.

The important for the given research values to test: rated peak impulse power; rated average power dissipation; the capacitance will be measured at a specified signal level, frequency, and bias voltage; rated forward surge current; temperature derating; temperature coefficient of breakdown voltage.

Rated forward surge current will be tested in the circuit of buck converter as follows (fig. 2):

1. Apply a half cycle of the rated forward surge current (IFSM) through the unidirectional component in the forward direction.
2. Repeat the test described in step 1, above, for a total of 10 times with a maximum interval between surges of 2 minutes.
3. Measure the stand-by current. The stand-by current shall not be greater than the maximum specified value after the surges.

To provide the test of the buck converter, the inductance (impedance) unbalance, the electric strength test, the magnetizing inductance measurements, and the temperature rise tests, the standard IEEE 388-1992 [3] will be used for non-isolated buck (step-down) converter topology.

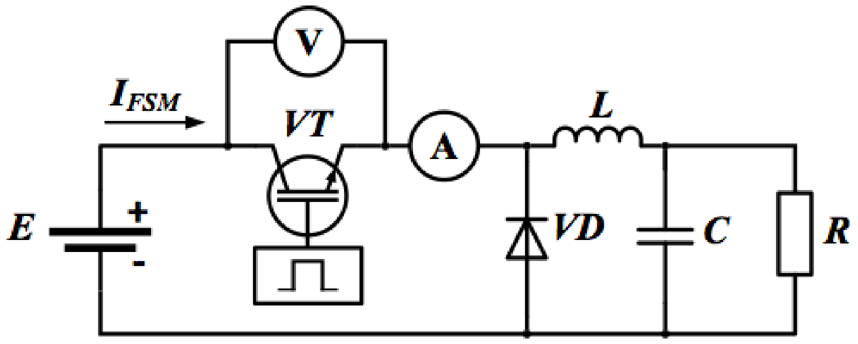


Fig. 2. Test circuit of buck converter for forward surge current: A – peak reading ammeter; V – peak reading digital voltmeter.

To create surge current and thermal protection system with transient waveform control using inductor magnetic core parameters changing, it is necessary to calculate and test the following parameters: the ratio of transformation, the inductance (impedance) unbalance, the electric strength, the magnetizing inductance, the transformer losses and capacitance (the control of induction by parallel magnetically dependent inductor circuit works in the same way as a normal transformer), temperature rise tests.

The measurements of the temperature rise and the inductance are the most important for providing the thermal and surge current protection system reliability.

The maximum temperature rise of a transformer can be measured by embedding a thermocouple at the hot spot of the coil. If this is not possible, the average temperature rise can be determined by measuring the resistance change of the inside winding of the coil. To determine the average coil temperature rise, it is necessary to use the following

$$t_2 = \frac{R_2}{R_1}(K + t_1) \quad K, \qquad (1)$$

equation:
where t2 is the mean temperature that produces a change of resistance, R2, in a coil from resistance, R1, established at temperature, t1. Temperatures are expressed in degrees Celsius. For copper wire whose volume conductivity is 100% and whose temperatures is between 0 °C and 125°C, K = 234.5.

The used pulse inductance measurement method for high-frequency power magnetics consists in determining inductance through the dynamic values of voltage and current under actual operating conditions of a switched circuit.

To do this, three values are needed:

1. *E* = Peak value of the voltage pulse, in V, across the inductor (or winding of interest) during time, t.
2. *t* = The increment of time, in s, between the 50% rise and fall voltage points of the voltage pulse.
3. *I* = Increment of current, in A, over time, t. It is assumed that this current ramp is essentially linear over this time.

The inductance of the winding can then be calculated:

$$L(\&H_{ys}) = \frac{E\ \ t}{I}. \qquad (2)$$

To calculate the junction temperature, the thermal response and the peak currents, and to analyze the failure modes of thyristor diodes and other semiconductor elements operating in pulse mode, that is required to test the developed protection means, the standard C62.37-1996 [4] will be used. To create a mathematical model of semiconductor components, the following parameters will be used: breakover current, breakover voltage, holding current, repetitive and non-repetitive peak on-state current and peak pulse current, off-state capacitance, off-state current, off-state voltage, on-state current, on-state voltage, breakdown current, critical rate of on-state current rise, forward current, forward voltage, impulse reset time, insulation resistance, lifetime rated pulse currents, peak pulse impulse current, switching current, switching resistance, maximum junction temperature, temperature coefficient of breakdown voltage, temperature derating, thermal resistance, transient thermal impedance, variation of holding current with temperature, virtual junction temperature.

The transient thermal impedance is the most important parameter for creating a thermal model of semiconductor devices. The purpose of transient thermal impedance test is to determine the power capability of a component for a specified power pulse duration, t. The thermal impedance, Z(t), permits the calculation of the power capability at different reference and junction temperatures. The value of Z(t) is calculated as follows:

transient thermal impedance junction to ambient for time interval *t*

$$Z_{JA(t)} = \frac{T_{JPK}\quad T_{A}}{P_{TOT}} \qquad (3)$$

transient thermal impedance junction to case for time interval *t*

$$Z_{JC(t)} = \frac{T_{JPK}\quad T_{C}}{P_{TOT}} \qquad (4)$$

transient thermal impedance junction to lead for time interval *t*

$$Z_{JL(t)} = \frac{T_{JPK}\quad T_{L}}{P_{TOT}} \qquad (5)$$

where: T_A is the ambient temperature reference; T_C is the case temperature reference, maintained at a constant value by cooling; T_L is the lead temperature reference, maintained at a constant value by cooling; T_{JPK} is the peak junction temperature, $0.8T_{JM} < T_{JPK} < T_{JM;}$ P_{TOT} is the power pulse amplitude; *t* is the pulse width of power pulse.

IV. Electro-Thermal Modelling

To analyze the electromagnetic and thermal processes during the converter operation, it is necessary to create a mathematical model, which will be describe them. The differential equations of the state were obtained to describe the electromagnetic processes. They are convenient for calculating the converter parameters depending on the temperature changes of the circuit components.

A general form of the equation can be written as:

$$\frac{dX}{dt} = AX + B \qquad (6)$$

where $X = \begin{vmatrix} i \\ u \end{vmatrix}$ – vector of state variables, A – matrix of coefficients, B – vector of external influence.

The solution of this equation can be represented as a matrix exponent [5]:

$$X = \overset{t}{\underset{mT}{}}\ e^{A(t\quad)}Bd \qquad (7)$$

where *T* – switching period of the converter transistors, *m* – period number, *t* – analyzed time of operation, *τ* – coefficient of integration.

The main value characterizing the matrix exponent is the eigenvalue of the matrix λ. To calculate λ, the following form should be used:

$$\det(A \quad I)=\begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}=0,\; I=\begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} \tag{8}$$

Analyzing the ratios of the switching frequency to the roots of the characteristic equation, the characteristics of the device such as bifurcation diagrams of the switching points, the dependence of the error signal on time in the steady state, and other parameters can be found [6]. The dependence of the transient's value of semiconductor power converters on the complex component of the characteristic equations roots is used, and the thermal motion of these roots is investigated.

For a buck converter connected to a constant load, the equation of the state for electromagnetic and thermal processes has the following view:

$$\begin{vmatrix} \frac{di_L}{dt} \\ \frac{du_C}{dt} \\ \frac{dT_{VT}}{dt} \\ \frac{dT_{VD}}{dt} \\ \frac{dT_L}{dt} \\ \frac{dT_C}{dt} \end{vmatrix} = \begin{vmatrix} \frac{r(T_{VT},T_{VD},T_L)}{L(T_L)} & \frac{1}{L(T_L)} & 0 & 0 & 0 & 0 \\ \frac{1}{C(T_C)} & \frac{1}{RC(T_C)} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{R_{thjcVT}C_{thjcVT}} & \frac{Z_{thDT}}{Z_{thjcVT}} & \frac{Z_{thLT}}{Z_{thjcVT}} & \frac{Z_{thCT}}{Z_{thjcVT}} \\ 0 & 0 & \frac{Z_{thTD}}{Z_{thjcVD}} & \frac{1}{R_{thjcVD}C_{thjcVD}} & \frac{Z_{thLD}}{Z_{thjcVD}} & \frac{Z_{thCD}}{Z_{thjcVD}} \\ 0 & 0 & \frac{Z_{thTL}}{Z_{thL}} & \frac{Z_{thDL}}{Z_{thL}} & \frac{1}{R_{thL}C_{thL}} & \frac{Z_{thCL}}{Z_{thL}} \\ 0 & 0 & \frac{Z_{thTC}}{Z_{thC}} & \frac{Z_{thDC}}{Z_{thC}} & \frac{Z_{thLC}}{Z_{thC}} & \frac{1}{R_{thC}C_{thC}} \end{vmatrix} \begin{vmatrix} i_L \\ u_C \\ T_{VT} \\ T_{VD} \\ T_L \\ T_C \end{vmatrix} + \begin{vmatrix} \frac{E\ s}{L} \\ 0 \\ \frac{Q_{VT}}{C_{thjcVT}} \\ \frac{Q_{VD}}{C_{thjcVD}} \\ \frac{Q_L}{C_{thL}} \\ \frac{Q_C}{C_{thC}} \end{vmatrix} \tag{9}$$

where $r = r_{VT}\ \ s + r_{VD}\ (1\ \ s) + r_L$; s – switching function; i_L, u_C where ; *s* – switching function; , –state variables: the inductor current and the capacitor voltage; the values *r, L, C* depend on the temperature; T_{VT}, T_{VD}, T_L, T_C – temperature of the components; elements of the main diagonal show thermal response of the components, to establish the thermal dependence between the converter elements, the corresponding values of thermal resistance are used; values Z_{th} for capacitors and inductors can be taken as constant; the values Z_{th} for transistor and diode junctions and between components are calculated and tested as Z_{jc}, Z_{ja}(VT) with Z_{ja}(VD) (standard C62.37-1996).

To calculate electromagnetic and thermal processes together using combined mathematical model, it is necessary to consider the integration step and the rate of the processes. In Table 1, different types of models are represented depending on the process rate.

Table I. Models Depending on the Process Rate

Processes	Devices	Fast models	Slow models
Electromagnetic processes	***Semiconductor***	*S, R, RS, R(I)S*	–
	Passive	*LC, L(I)C(U)*	–
Thermal processes	***Semiconductor***	*R(Ti)*	*R(Tcs)*
	Passive	–	*L(T)C(T)*
Electro-thermal processes	***Semiconductor***	*R(Ti)S, R(Ti,I)S*	*R(Tcs)S*
		R(Ti,Tc)S, R(Ti,Tc,I)S	
	Passive	–	*L(T(P))C(T(P))*
		L(T(P),I)C(T(P),I)	

In this research the combined model with different rates of processes *R(Tj,Tc)SL(T(P))C(T(P))* with possibility to expand to *R(Tj,Tc,I)SL(T(P),I)C(T(P),I)* is used.

Transformation of the state equation into a system of two equations, where the first equation refers to fast electromagnetic processes, and the second one to the slow thermal processes, which are associated with the heating of passive components, cases and radiators of semiconductor devices, gives the following form:

$$\begin{aligned} \frac{dX_1}{dt} &= A_1X_1 + B_1 \\ \frac{dX_2}{dt} &= A_2X_2 + B_2 \end{aligned} \quad . \tag{10}$$

In this system of the equations, the coefficients matrix and vectors of external influence are not static coefficients, but depend on the temperature and electromagnetic state of the system. It is shown in the following form using diakoptics solutions [7]:

$$\begin{aligned} \frac{dX_1}{dt} &= A_1 \quad X_1 + B_1 \\ \frac{dX_2}{dt} &= A_2 \quad X_2 + B_2 \quad . \\ A_1, B_1 &= A_1, B_1 + f(X_2) \\ X_2 &= X_2 + g(P_1(X_1)) \end{aligned} \tag{11}$$

where the values of the coefficient matrix of the first equation depend on the temperature of the corresponding components calculated in the second equation, and the values of the dissipation power of the components of the second equation (P1) are determined by the results of calculations according to the first equation.

Due to the slowness of the passive components thermal processes, the thermal change of the parameters of the coefficient matrices and the vector of external influence for electromagnetic processes can be calculated discretely:

$$\frac{dX_1}{dt} = A_1 \quad X_1 + B_1$$

$$\frac{dX_2}{dt} = A_2 \quad X_2 + B_2$$

$$A_1, B_1[nT] = A_1, B_1[(n \quad 1)T] + \quad A_1[X_2], \qquad (12)$$

$$P_2[nT] = P_1(X_1[nT])$$

where *n* = (1, 2,…) – communication step between equations; h – the coefficient of the step, which depends on the time, at which the slow process equation gets a significant influence on the fast process equation.

The actual problem of integrating the system of differential equations is the choice of integration step. Choosing a big step violates the stability of the calculation method, the choice of a small step causes an overestimated cost of the calculation.

To optimize the calculations, the matrix is divided into an independent temperature component matrix with static parameters and a temperature-dependent component matrix with dynamic parameters:

$$\frac{dX}{dt} = \left(A_e + A_t\left[nT\right]\right)X + B\,. \qquad (13)$$

Therefore, it can be assumed that the equation of communication is linear and has the form. $X_1 = kX_2$.

Considering this linearity and the reaction inertia of slow heat processes to fast electromagnetic ones, the step of communication between equations must correspond to the magnitude when rapid processes begin to significantly affect the slow processes.

$$A_1[nT] = A_1[(n \quad 1)T] + \quad A_1(X_2[mh_2]) \qquad (14)$$

$$P_2[nT] = P_1[mh_1] \quad ,$$

where *h*1 – transferring data step from the equation of thermal processes to the equation of electromagnetic processes; h2 – transferring data step from the equation of electromagnetic processes to the equation of thermal processes.

Fig. 3 graphically represents the current and the temperature, and their interconnections using the constituent equations of communication.

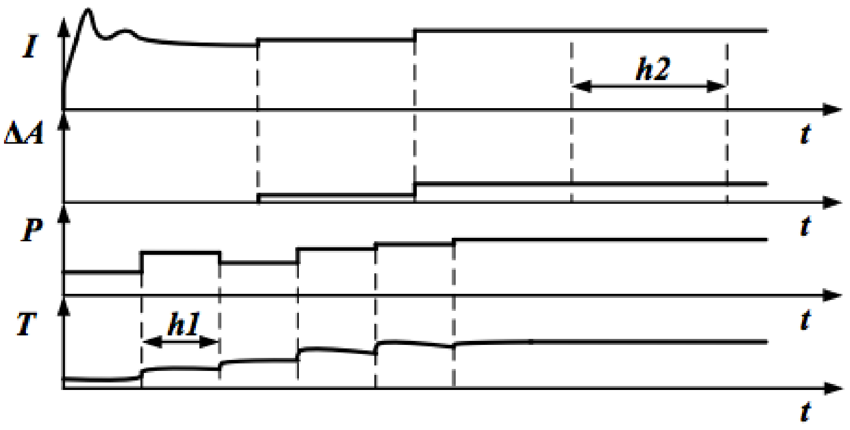


Fig. 3. Current and temperature in communication

The eigenvalues determine the oscillation and time scale of transient processes. For rigid systems, the ratio of roots is significant. Fig. 4 shows the zone of suitable values for the implicit Euler method, where μ and v are eigenvalues of electromagnetic and thermal matrices.

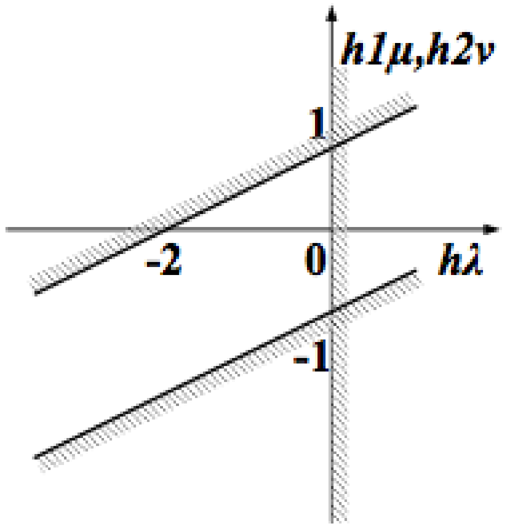


Fig. 4. Zone of implicit Euler method stability

In a case of selecting an integration step according to the equations $h_{\min} + 2h_{\max} < 2,\ h_{\max} \quad 2h_{\min} < 2,\ h \quad < 0$, the most suitable value can be calculated as:

$$\frac{h_1}{h_2} \quad - = \frac{2}{1}. \qquad (15)$$

The stability zone of the computational process is not constant. The boundaries of the zone dynamically change with the thermal change of component parameters. Correspondingly, the integration steps and the step of equations of communication will be also changed. Consequently, at each recalculation of the temperature-dependent component matrix, it is necessary to determine the integration steps. Acceleration of the adjustment process is achieved in two stages:

1. The choice of the communication equations step, considering the sensitivity to the thermal motion of the eigenvalues

$$\frac{S_{\ i}}{T} \quad 0.$$

2. Finding the stability zone of the integration method.

In some cases, to develop the thermal protection systems, it is sufficient to analyze the thermal motion of the characteristic equation roots.

Using the bisection matrix formulas based on binary vectors [7], getting:

$$\begin{aligned} &\det(A \qquad I)=\det(A_e \qquad I)+ \\ &+ \quad (\ 1) \quad {}_e(d_i)\ {}_t(\overline{d_i}) \qquad ^2+\det(A_t \qquad I) \end{aligned}, \qquad (16)$$

where:

$$\begin{aligned} &(\ 1) \quad {}_e(d_i)\ {}_t(\overline{d_i})=a_{11}\ \ a_{22}(\ \ ) \\ &a_{12}\ \ a_{21}(\ \ )\ \ \ a_{21}\ \ a_{12}(\ \ )+a_{22}\ \ a_{11}(\ \ ) \end{aligned}. \qquad (17)$$

As example, in case of the buck converter in the open state of the transistor, : $mT \quad T \quad mT+DT:$

$$\begin{aligned} &\begin{vmatrix} I \\ U \end{vmatrix} = \int_{mT}^{t} e^{A_1(t\quad)} \begin{vmatrix} \frac{E}{L} \\ 0 \end{vmatrix} d \quad = \\ &= e^{A_1(t\ \ mT)} \begin{vmatrix} I(mT) \\ U(mT) \end{vmatrix} + A_1^{\ 1}\left(e^{A_1(t\ \ mT)} \quad I\right) \begin{vmatrix} \frac{E}{L} \\ 0 \end{vmatrix} \end{aligned}. \qquad (18)$$

On the interval of the closed state of the transistor,

$$mT+DT \quad T \quad (m+1)T:$$

Eigenvalues:

$$\begin{vmatrix} I \\ U \end{vmatrix} = \int_{mT+DT}^{t} e^{A_2(t\quad)} d \quad = e^{A_2(t\ \ mT\ \ DT)} \begin{vmatrix} I(mT+DT) \\ U(mT+DT) \end{vmatrix}. \qquad (19)$$

$$_{1,2} = \ \frac{1}{2}\ \ \frac{r}{L}+\frac{1}{RC} \pm \sqrt{\ \frac{r}{L}+\frac{1}{RC}\ ^{2} \quad \frac{4}{LC}\ \ \frac{r}{R}+1\ } \ , \qquad (20)$$

where $_{\min}$ – minimal real component of eigenvalue, which determines the length of the transients, being a value inversely proportional to the time of regulation.

The type and duration of the transients depend on the distance of the eigenvalues to the imaginary axis, which calculates as:

$$tg \quad = \frac{\mathrm{Im}(\ \ )}{\mathrm{Re}(\ \ )}. \qquad (21)$$

Characteristic equation:

$$^2+b \qquad +c=0, \qquad (22)$$

where:

$$b= \ \ a_{11} \quad a_{22} \quad a_{11}(\ \ ) \quad a_{22}(\ \ ), \qquad (23)$$

$$\begin{aligned} &c=a_{11}a_{22} \quad a_{12}a_{21}+a_{11}(\ \ )\ a_{22}(\ \ )+a_{11}a_{22}(\ \ )+ \\ &+a_{22}a_{11}(\ \ ) \quad a_{12}(\ \ )a_{21}(\ \ ) \quad a_{12}a_{21}(\ \ ) \quad a_{21}a_{12}(\ \ ) \end{aligned}, \qquad (24)$$

Characteristic equation can be written as:

$$^2+\frac{b}{\ } \qquad + \quad ^2= \quad ^2+B \qquad + \quad ^2=0, \qquad (26)$$

$$=\sqrt{\ _1\ \ _2\ }, \qquad (27)$$

B – describes the transition form, – the time scale of the process: = *t*.

V. Adaptive Thermal and Surge Current Protection Systems

One of the most dangerous operation mode in power converters is restart of the heated device. Since the junction temperature of semiconductor components increases, their boundary parameters are reduced. Due to this understatement of the parameters during restart, the current value and the thermal spikes (tg(φ)) of the transient process are important parameters, since they can determine the accident rate of this process. To reduce the temperature spikes, a thermal and surge current system based on decreasing the oscillating component of the transient process is proposed (Fig. 5) [8].

The system implements the temperature feedback of the converter (C) through the microcontroller (MC) containing the thermal models. The variation of the smoothing filter inductance is provided by the current regulation through magnetically connected inductor coil, which is determined by the MC and amplified by the operational amplifier (OA). To calculate the stabilization current value, it is required to consider the temperature of filter inductor coil. To do this, it is necessary to approximate test data taken using IEEE

388-1992 standard into mathematical model. For these purpose, a regression analysis was applied, and the temperature dependences of the coil were given as ,

$$(\ _L)=a_n\ ^n+a_{n\ 1}\ ^{n\ 1}+\ldots+a_1\ \ +a_0=\quad(\ _L)+$$

where μ – magnetic conductivity at 25° C; $\theta = t° - 25$.

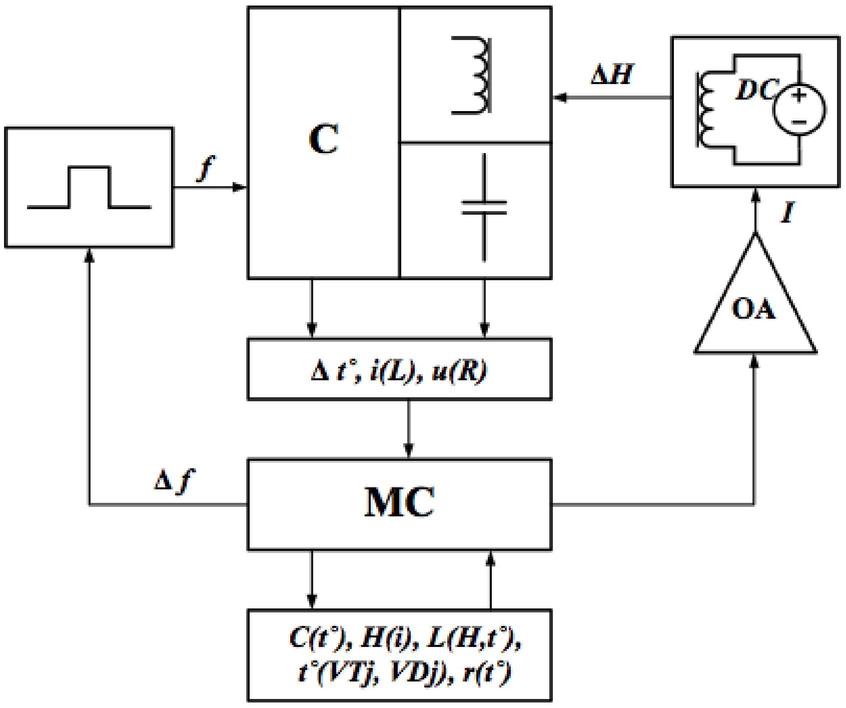
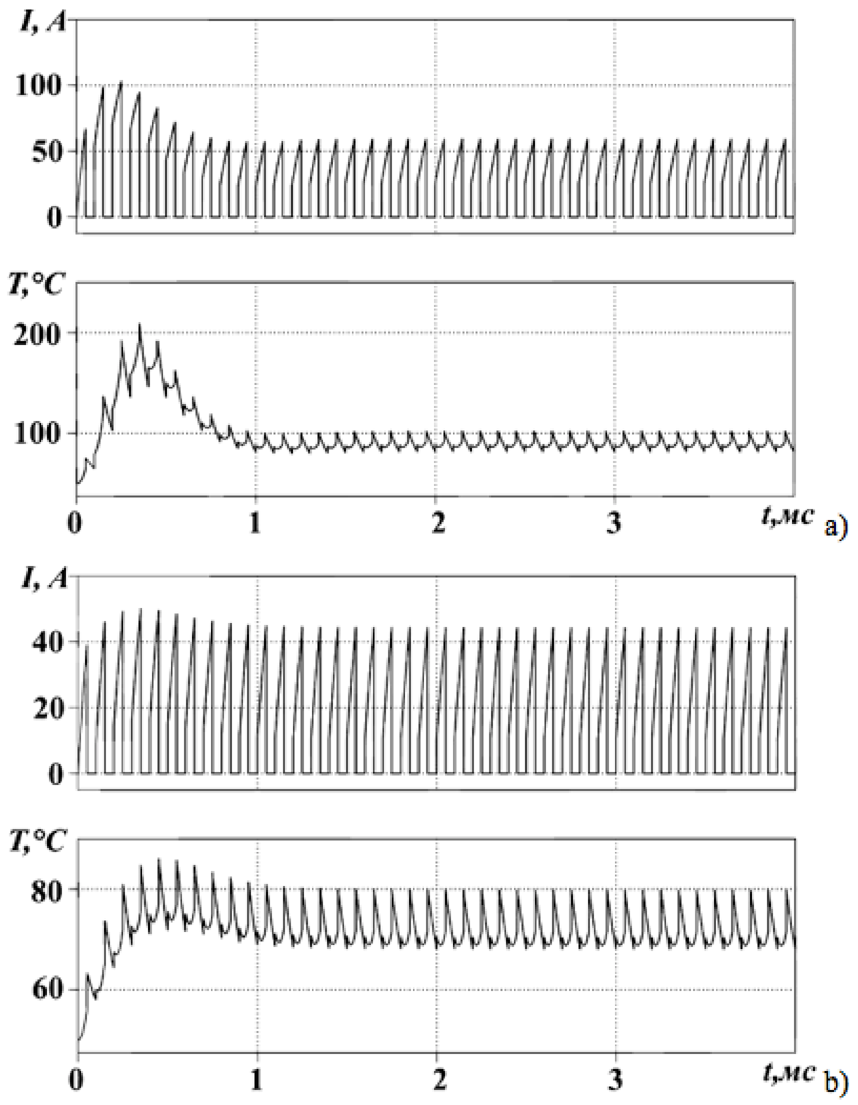


Fig. 5. Thermal and surge current protection with transients' waveform stabilization

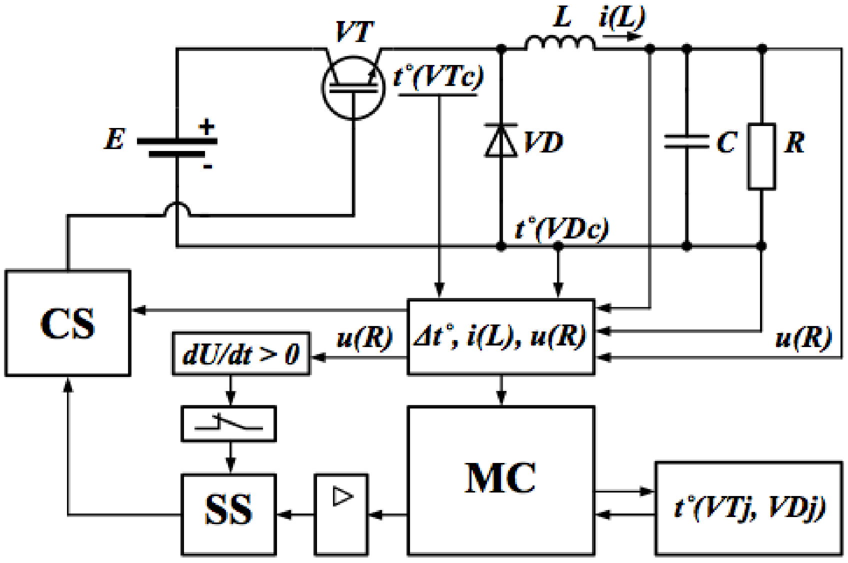


(bottom left) *Fig. 6. Buck converter junction current and temperature: a) normal transient; b) transient obtained using the protection system, which decreased the thermal spike to extended normal operating range (C62.35-2010)*

The parameters of electromagnetic processes were also corrected by changing the switching frequency of the converter input transistor. This double correction ensures that the parameters of the semiconductor junctions are within the limits of the maximum permissible values when the temperature changes. Using the means of MATLAB/Simulink [9, 10] and Plecs [11], the simulation of the circuit was carried out, and its effectiveness was confirmed (Fig. 6).

To solve the problem of junction thermal spikes during a short circuit and a current drop, a system for restarting a temperature dependable smooth start after a short circuit is proposed (Fig. 7).

During short circuit, the load voltage decreases sharply. Upon short circuit exclusion, the output voltage is registered, which is a signal for the restart of the smooth start system. To control the duration of smooth start, a microcontroller (MC) containing the electro-thermal models is used. Based on the data of the temperature sensors, on the inductor current and the load voltage, the semiconductor junction temperature is calculated. The signal from the MC goes through the system of smooth start (SS) to the control system (CS) by specifying the duration of a smooth start with the coefficient of pulse filling, depending on the junction temperature. The simulation results confirmed the possibility of reducing the temperature spike of the buck converter transistor junction from 180°C to 85°C (fig. 8).



System of surge current and thermal protection with restart of temperature dependable smooth start after short circuit

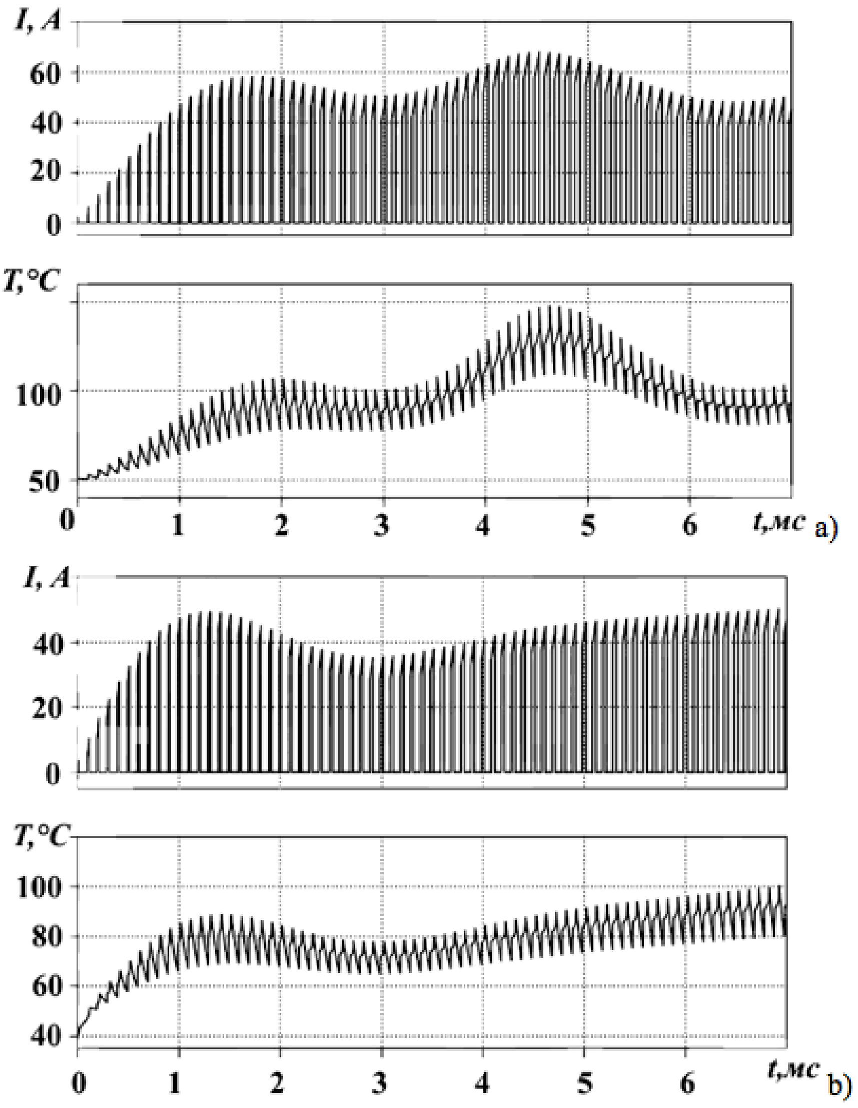


Fig. 8. Transistor junction current and temperature during restart of the smooth start system: a) without thermal feedback; b) using adaptation of the smooth start duration to the transistor junction temperature and current, which decreased the thermal spike to extended normal operating range (C62.35-2010)

VI. Practical Implementation of the Systems

The peculiarity of modern surgery lies in wide implementation of electrocoagulation equipment. The application of such devices makes it possible to substantially reduce the duration of surgery intervention, the blood loss and the time of postoperative recovery. The development of new types of electrocoagulators enables the use of new methods of surgery. One of the most relevant problems of the development and use of such equipment is its reliability.

The research is devoted to the development of surge current and thermal protection equipment to prevent malfunction of power converter, which is a part of electrocoagulator.

The specific feature of operation of such type of medical devices is the use of repeated intermittent modes characterized by both idle mode and short circuit.

The electrical modes of operations of the elements of prototype electrocoagulator were studied. The calculations of extreme modes of operation of semiconductor elements were carried out. The parameters of LC-filter were determined, and the types of magnetic throttle materials were suggested as well as the capacity providing the permissible spikes of semiconductor junction current. The smooth start system with adaptive time constant limiting the spikes of junction current of the electrocoagulator converter was used. Fig. 9 shows the difference between prototype electrocoagulator smooth start system and adaptive smooth start system, described earlier.

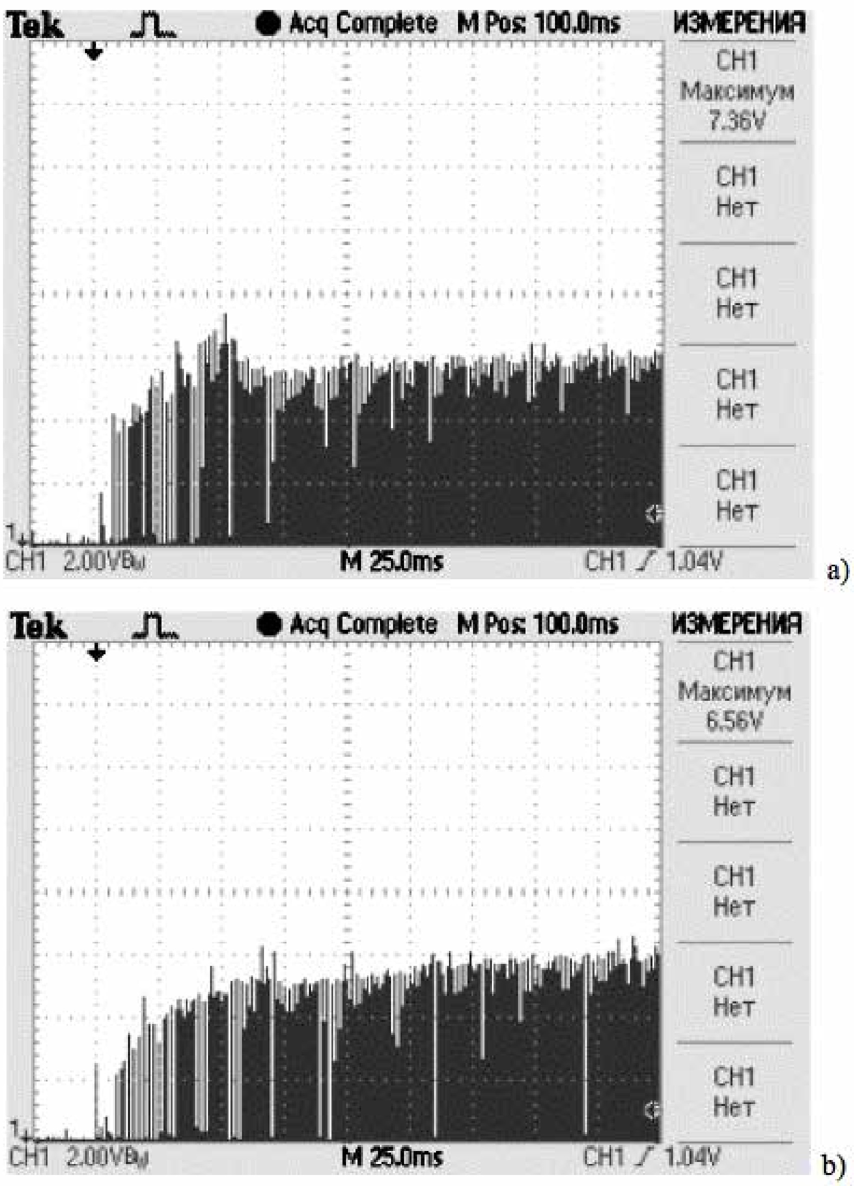


Fig. 9. Scope data of electrocoagulator operation: a) using smooth start system; b) using smooth start system with junction temperature feedback

The use of developed surge current and thermal protection systems made it possible to substantially increase the reliability of the welding electrocoagulator. The number of failure of power semiconductor elements is 14 times reduced to 1.2% comparing to the prototype electrocoagulator.

VII. Conclusion

The task of designing the surge and thermal protection means with thermal feedback, providing the permissible limits of heat and electric parameters, for semiconductor power non-isolated converter was solved due to carrying out a combined analysis of its electromagnetic and thermal processes.

Using the standards C62.35-2010, IEEE 388-1992, C62.37-1996, the calculation and check of temperature derating and temperature coefficients of breakdown voltage, the test of inductance unbalance and magnetic core parameters, the analysis of temperature rise, the calculation of junction temperature, thermal response, peak currents, and the analysis of failure modes of pulse semiconductor elements, were done.

Based on suggested mathematical model of the semiconductor converter, which considers the thermal dependence of the parameters of active and passive components, the effect of temperature changes of the components' parameters on the electromagnetic processes and the limiting operation modes of the power switches was estimated.

The developed thermal protection systems were simulated in the combined Plecs/MATLAB/Simulink environment. The simulation of the protection system with the adaptation of the smooth start time constant to current and temperature values showed the possibility of reducing the thermal spike on the transistor junction from 180°C to 80°C. The simulation of the system based on the normalization of the parameters of the passive components depending on the temperature changes showed the possibility of reducing the thermal spike on the transistor junction from 210°C to 85°C. The simulation results confirmed the advisability of using the developed protection systems in semiconductor converters. The system of protection with thermally depending smooth start adaptation is used in electrocoagulation devices.

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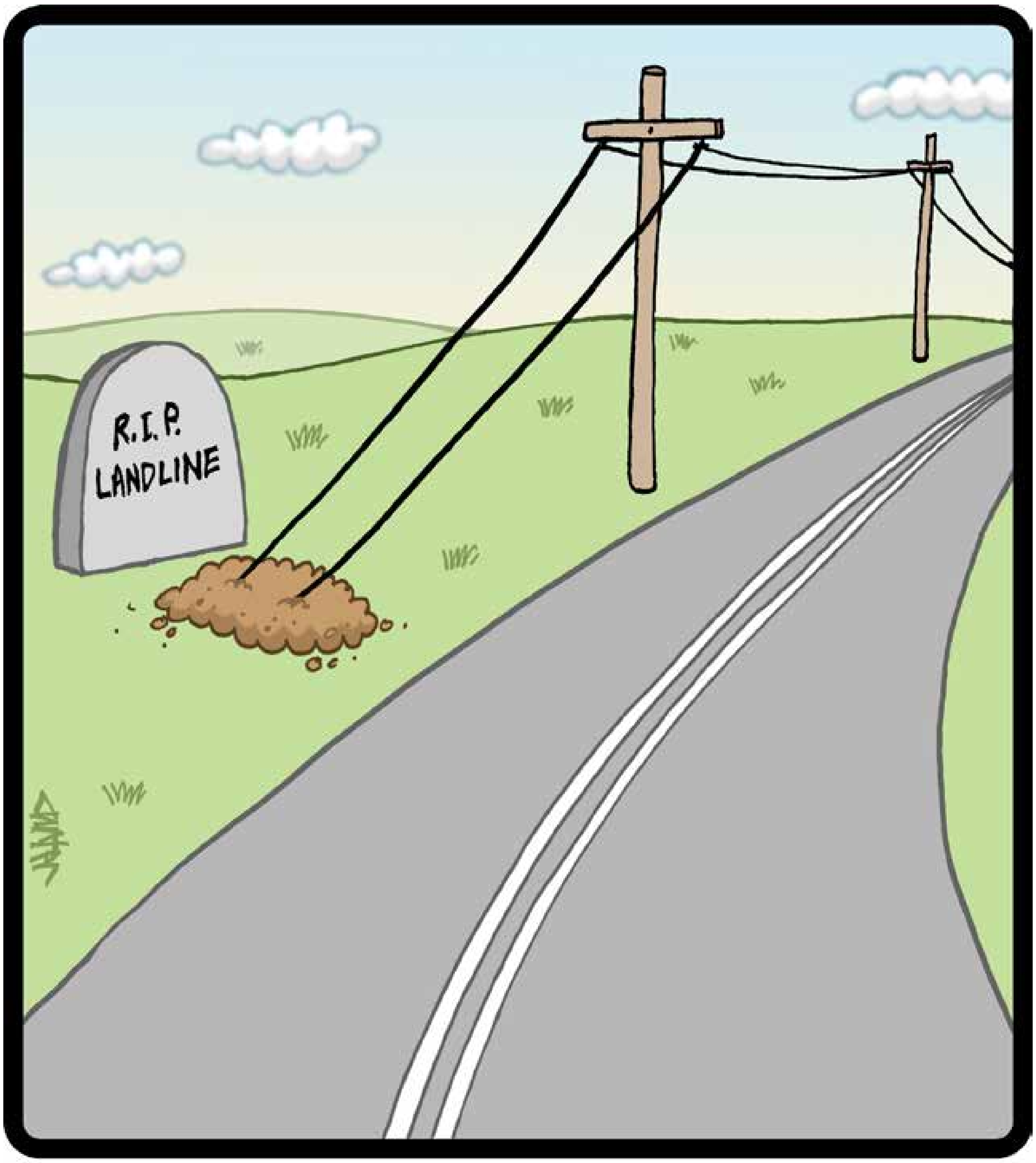

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