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Abstract

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Modern Vehicle Architectures

Advanced Embedded Systems

# Introduction

Since the first modern automobiles produced by Karl Benz and Henry Ford, the automotive industry underwent continuous growth and development, becoming one of the largest industries worldwide. One of the most important drivers of the automotive industry is the constantly increasing demand for functionality, comfort, safety and performance inside the vehicle, matched to the rapid development of electronics and software technologies [1]. During the last decades more and more functions of the vehicle moved away from mechanical and hydraulically technologies and adopted electronic counterparts. Examples of such functions are the steering, transmission and wipers. Moreover, new functions were added to the vehicle once certain embedded technologies became available, such as the electronic break system and the electronic stability control. In the same time, governmental regulations reading transportation safety and pollution led to the advancement of specific technologies aimed towards low power consumption and environmentally friendly vehicles. All these factors contributed to the development of embedded systems and software technologies for the automotive industry.

## Early stages

Early iterations of vehicle architectures comprised a relatively small number of electronic control units (ECUs). Each of the ECUs implemented a function of the vehicle completely. Although limited, the communication between ECUs was implemented using point-to-point connections [1]. In later years, the number of ECUs steadily increased as the technology became available, thus the number of connections grew proportionally. The development of hardware components made possible the integration of new functions and even domains into the vehicle, such as radio equipment for in-vehicle entertainment. Adding new features and functions had a direct impact on the hardware requirements of the embedded systems regarding processing speed and memory size. The software size within the vehicles rapidly increased from around 1KB to almost over 2MB in just 20 years [1]. Other features required completely new hardware to be integrated, such an example being the introduction of GPS in vehicles for safety and security, and much later for navigation purposes. Even though such hardware was available, it soon became obvious that it was not suitable for the road conditions in which the embedded systems within the vehicle should operate. Soon, silicon providers started producing automotive graded integrated circuits (ICs) which met the requirements of temperature, vibration, shock, electromagnetic compatibility and electrostatic discharge of the automotive industry.

## Current development

Vehicle became complex distributed embedded systems consisting in large numbers of sensors, actuators and processing units. Each functions of the vehicle moved from being stand-alone implemented in a single ECU to being distributed across several electronic control units (ECUs). The number of ECUs in a vehicle was also subject to growth, averaging in current vehicle architectures to around sixty [1][2]. Moreover, the data exchange demand increased as well since more and more functions required inputs from different parts of the vehicle. For example, modern vehicles employ dynamic volume control of the media player with respect to the vehicle speed. The volume control and the vehicle speed reading are implemented in different ECUs; thus, data exchange is required. The previous approach of point-to-point connections between ECUs proved inefficient and the need for large bandwidth communication busses emerged. The advantages that communication busses have over the traditional interconnections are numerous, including reduced weight of cables and, implicitly, reduced cost. In fact, the wiring and the harnesses required to connect various ECUs proved to be the most expensive component before the year 2000, wiring sometimes peaking at a few kilometres in length [3].

The early vehicle communication networks were not standardized and were based on proprietary circuitry and mostly Universal Asynchronous Receiver Transmitter (UART) interfaces. With the increasing vehicle functionality and competition on the market, the automakers started employing external suppliers to develop more complex and standardized communication interfaces [4]. The standardization of protocols and in-vehicle communication allowed for more complex systems to be integrated and led to the so-called open architecture of the modern vehicles. Bosch developed one of the first vehicle networks – the CAN (Controller Area Network) around the year 1980, which was first integrated into production vehicles by Mercedes-Benz in 1992.

## Future trends

Latest trends in the automotive industry support even more demanding requirements such as vehicle communication with the external world. Most notable examples are internet connectivity, vehicle-to-infrastructure and vehicle-to-vehicle capabilities. Such requirements add constraints to the vehicle architecture and communication systems and often require a change in paradigm to be feasible.

# Vehicle functional domains

Vehicle functions and their implicit hardware, software and mechanical components are usually split into domains by Original Equipment Manufacturers (OEMs). Each domain has its own requirements in terms of safety and performance and communication. The four domains that are commonly referred by OEMs and suppliers in the industry are *powertrain*, *chassis*, *body* and *infotainment* [1]. Each domain comprises several ECUs which co-operate to achieve its specific requirements. Due to the common communication requirements shared by all the ECUs belonging to a certain domain, a single communication network is sufficient to implement the intra-domain communication. This grouping of ECUs with shared communication requirements into domains increases the robustness of the overall system by separating the communication as well into critical and non-critical communication.

Although each domain is responsible for driving certain functions of the vehicle, it is almost always the case that inter-domain communication is required as well.

# Architectures

## Gateway architecture

## Domain controlled architecture

## Operating systems

The AUTOSAR standard is a joint effort aimed towards an open software architecture and comprises a set of specifications for various components and their interfaces. One of the main drivers of the AUTOSAR standards is the decoupling of software from hardware to enable software reuse [9]. Since the AUTOSAR Release 4.0 in 2009, the AUTOSAR standard supports multi-core systems allowing either one AUTOSAR instance to control all the cores or multiple instances running on dedicated cores [10]. Implementation of the AUTOSAR specifications are good software candidates for the domain controllers and body controller since they already support standardized interfaces and allow for software reuse.

# Communication systems

In-vehicle data communication has been a key component to the modern vehicles. Whether it is inter-ECU or intra-ECU communication, the parameters of data transfer play a critical role in the performance of each individual function of the vehicle and the overall system. The communication technologies integrated into modern vehicles are standardized and described in detail at electrical, physical, software and mechanical level. The characteristics of the physical layer impact the throughput and the maximum data rates. The mechanical aspects of the connection contribute to the cost and weight reduction of the vehicle while also affecting the behaviour of the connection in the presence of shock, wide temperature ranges, vibrations and other environmental constraints. The electrical aspects influence both the performance of the data transfer and the power consumption while the software design of the connection transmission and reception sides impact the resources consumption for the processing units (CPU load, memory, etc.).

# Domain controlled architectures of the future

This chapter describes the state-of-the-art next generation in-vehicle networking standards proposed and described in [5] and presents the potential use of automotive Ethernet as backbone for the domain-controlled architecture as described in [6].

## Limitations of current technologies

The increase in vehicle functions both in the infotainment and the driver assistance systems domains exploits to the limit the currently available in-vehicle communication technologies in terms of bandwidth and performance. Following the development of advanced driver assistance systems (ADAS) and other technologies aimed towards autonomous driving, it became obvious that as the driver interaction with the vehicle will be reduced, the potential and opportunities for in-vehicle entertainment and even workspace functions will rapidly grow. Thus, the vehicle will need to support many more functions such as high-speed internet connectivity, high quality media streaming and playback, workspace applications and fully featured connectivity with the external environment. These features require more bandwidth than it is currently available using traditional communication and in-vehicle networking technologies.

In the traditional gateway vehicle architecture, the communication between different domains in routed through special ECU called the *gateway*. One of the purposes of the gateway ECU is to make sure that there is information flow across domains and across their different networks. In addition, the gateway performs conversions of messages between different protocols (e.g. CAN to LIN, MOST to CAN, etc.) when necessary. Furthermore, the gateway is responsible for delivering diagnostic requests and responses between domains and the On-Board Diagnostic (OBD) clients.

Historically, the advantages of such a gateway architecture are both in terms of lifetime and in terms of flexibility, enabling easy replacement of damaged parts as well as enhanced robustness for adjusting the system throughout the production stages [5]. However, the before described advantages add overhead to the communication between different parts of the vehicle and lead to overloading and interferences.

To solve the overloading problem and, possibly, to address the timing constraints imposed by the processing of various critical sensor information such as video camera inputs, a possible solution is to cluster vehicle functions into single ECUs [5]. With this approach, also depending on the various functions of the vehicle, the signal acquisition from sensors, the processing and the decision are performed within the same local system, thus reducing the amount of time required to perform actions based on sensor input. Moreover, this approach reduces the number of ECUs in the vehicle and the number of inter-connections, potentially saving production costs.

Such an architecture imposes two main disadvantages. Foremost, centralizing functions demands increased processing power to meet the functional requirements of the applications. Such processing power is not available at low cost and more expensive high-performance hardware platforms are necessary. Secondly, by grouping all functionality related to certain features of the vehicle into a single place, some redundancy is lost and must be dealt with while also complying with the automotive standards [5].

## Domain controlled architecture structure

Following the functional classification of domains within the vehicle, a new domain-controlled architecture is described in [5] and [6], which attempts to address the limitations of the traditional gateway architecture while preserving the flexibility, scalability and cost efficiency. The domain-controlled architecture partitions functions and ECUs into domains which are further abstracted by a so-called *domain controller*. Domain controllers are ECUs acting as gateways for their associated domains by managing the intra-domain communication networks and routing higher-level messages within and outside of the domains. Furthermore, by acting as integration platforms for the intra-domain ECUs, domain controllers save integration and development time [5]. Functionality is also grouped within a domain depending on the required flexibility. Critical software is integrated into the domain controllers and is always available while other lightweight functions are integrated into slave ECUs and can be turned on and off at any time for both flexibility and reduced power consumption.

The domain controllers further communicate and form a network together with the central gateway ECU which is commonly referred to as the *body controller*. The communication between the body controller and the domain controllers is realized using point-to-point connections for high speed and reliability as well as meeting the time constraints imposed by critical message paths between domains [7]. The communication within a domain is still realised using traditional communication systems such as CAN, LIN, FlexRay and MOST. Each domain implements intra-domain communication accustomed to its performance needs.

## Hardware implementation

The performance and time requirements of the domain-controlled architecture enforce stringent hardware requirements to support its functions. The demand for high processing power collides with the general requirement of low power consumption, therefore a compromise solution must be achieved. Both [5] and [7] propose the use of highly optimized multi-core CPUs to meet both requirements. Current architectures do contain multi-core processors but the software they run is not optimized for parallel processing since the tasks performed on multiple cores are stand-alone. An important step towards a domain-controlled architecture is, thus, the optimization of most of the software processes to accustom parallel programming [5] [8].

In terms of CPU load, the most loaded ECUs of the vehicle are the body controller – responsible for routing the inter-domain traffic – and the domain controllers – responsible for both routing intra-domain traffic and forwarding messages to and from within the domain. For these ECUs a completely new hardware platform needs to be used which integrates comprehensive communication technologies and the required processing power. The embedded microcontrollers must also be optimized to support the communication requirement. The inter-domain message routing can be performed without CPU support on a dedicated controller. To reduce the main memory access, the routing controller can be equipped with its own secondary RAM which is used to store the message buffers. The transfer of message buffers to the main memory can be done via DMA to further preserve the CPU availability for other tasks.

## Ethernet backbone

Traditional communication systems are not suitable for the increasing bandwidth demands of the future automotive applications such as ADAS and infotainment. Furthermore, in a domain-controlled architecture the inter-domain communication has even more stringent time constraints. Ethernet has been identified as a possible candidate for replacing traditional networking technologies in certain areas of the vehicle where bandwidth is essential. The main advantage of Ethernet over building a completely new networking protocol is that it reuses a lot of already validated software stacks. On the other hand, Ethernet is not inheritably automotive compliant and certain modifications and adaptations are required for safe use within the vehicles [8].

Ethernet is based on point-to-point communication routed through switches. Such approach proves to be more efficient in terms of bandwidth than the priority mechanisms employed by CAN and FlexRay and can be applied to inter-domain communication. The IEEE specifications for Ethernet describe the physical and the MAC layers of the protocol, supporting data rates of 10Mbps up to 10Gbps. The upper layers of the OSI stack are also specified for specific applications such as audio/video streaming, addressing timing and synchronization and other features of the AVB (Audio Video Bridging) systems [8]. Resolving the time constraints is not straight forward since Ethernet is not particularly designed for time division multiple access. The real-time performance and the Quality of Service requirements still need to be addresses.

Automotive Ethernet can be used not only as backbone for the inter-domain communication network, but for other functions which require high bandwidth. One such application is the diagnostic access which must support re-flashing and re-calibration of the ECU memories. In later years Ethernet has been extensively used as interface for its much higher bandwidth than traditional interfaces. Another successful application is within ADAS where an increasing number of cameras are being used to scan the environment. In the initial stages of ADAS, when a single camera was used, the image data was transferred via LVDS, however, this method becomes impractical when multiple streams must be transmitted simultaneously. Ethernet offers the required bandwidth together with additional advantages of low power consumption through the LPI (Low Power Idle) mode and the PoE (Power over Ethernet) function. Recently, automotive Ethernet has been used in the infotainment domain as well, including higher layers such as AVB (Audio Video Bridging).

To comply to the time constraints, automotive Ethernet must also be real-time. In this respect, three major concepts of real-time ethernet have been revised: *token-based*, *bandwidth-limiting* and *time-triggered* [11]. TTEthernet is an implementation of the time-triggered ethernet concept based on a TDMA (Time Division Multiple Access) scheme which is proven to meet the real-time requirements imposed by the automotive industry [12].

Since some of the intra-domain communication is supported by CAN networks, the IEEE 1722a mapping has been developed to support CAN messages encapsulation into Ethernet frames [9].

[[1]](#footnote-1)

High-bandwidth multimedia link for next generation automotive architectures

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***Abstract*—These instructions give you guidelines for preparing papers for IEEE Transactions and Journals*.* Use this document as a template if you are using Microsoft *Word* 6.0 or later. Otherwise, use this document as an instruction set. The electronic file of your paper will be formatted further at IEEE. Paper titles should be written in uppercase and lowercase letters, not all uppercase. Avoid writing long formulas with subscripts in the title; short formulas that identify the elements are fine (e.g., "Nd–Fe–B"). Do not write “(Invited)” in the title. Full names of authors are preferred in the author field, but are not required. Put a space between authors’ initials. The abstract must be a concise yet comprehensive reflection of what is in your article. In particular, the abstract must be self-contained, without abbreviations, footnotes, or references. It should be a microcosm of the full article. The abstract must be between 150–250 words. Be sure that you adhere to these limits; otherwise, you will need to edit your abstract accordingly. The abstract must be written as one paragraph, and should not contain displayed mathematical equations or tabular material. The abstract should include three or four different keywords or phrases, as this will help readers to find it. It is important to avoid over-repetition of such phrases as this can result in a page being rejected by search engines. Ensure that your abstract reads well and is grammatically correct.**

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INTRODUCTION

I

N recent years the increasing development of the Advanced Driver Monitoring Systems (ADAS) and the autonomous driving technologies proved that fully autonomous vehicles are feasible and will eventually reach the market. In parallel to the development of such intelligent systems to control and monitor de vehicle functions, the interaction of the driver with the vehicle will steadily decrease, leading to a rising demand for sophisticated infotainment systems. It becomes more and more evident that customers expect the same level of comfort and functionality in vehicles as in their homes. This demand encourages carmakers and suppliers to research, develop and integrate new technologies into the already complex vehicles. Both ADAS and infotainment domains have constringent requirements in terms of bandwidth, performance and real-time behavior and both cannot be accustomed by the traditional gateway architectures employed in most of the currently in production vehicles [9]. To address the lack of bandwidth in the current and traditional architectures, the domain-controlled architecture has been proposed in conjuncture with an Ethernet backbone [7] [11].

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To insert images in *Word,* position the cursor at the insertion point and either use Insert | Picture | From File or copy the image to the Windows clipboard and then Edit | Paste Special | Picture (with “float over text” unchecked).

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*Abbreviations and Acronyms*

Define abbreviations and acronyms the first time they are used in the text, even after they have already been defined in the abstract. Abbreviations such as IEEE, SI, ac, and dc do not have to be defined. Abbreviations that incorporate periods should not have spaces: write “C.N.R.S.,” not “C. N. R. S.” Do not use abbreviations in the title unless they are unavoidable (for example, “IEEE” in the title of this article).

*Other Recommendations*

Use one space after periods and colons. Hyphenate complex modifiers: “zero-field-cooled magnetization.” Avoid dangling participles, such as, “Using (1), the potential was calculated.” [It is not clear who or what used (1).] Write instead, “The potential was calculated by using (1),” or “Using (1), we calculated the potential.”

Use a zero before decimal points: “0.25,” not “.25.” Use “cm3,” not “cc.” Indicate sample dimensions as “0.1 cm × 0.2 cm,” not “0.1 × 0.2 cm2.” The abbreviation for “seconds” is “s,” not “sec.” Use “Wb/m2” or “webers per square meter,” not “webers/m2.” When expressing a range of values, write “7 to 9” or “7-9,” not “7~9.”

A parenthetical statement at the end of a sentence is punctuated outside of the closing parenthesis (like this). (A parenthetical sentence is punctuated within the parentheses.) In American English, periods and commas are within quotation marks, like “this period.” Other punctuation is “outside”! Avoid contractions; for example, write “do not” instead of “don’t.” The serial comma is preferred: “A, B, and C” instead of “A, B and C.”

If you wish, you may write in the first person singular or plural and use the active voice (“I observed that ...” or “We observed that ...” instead of “It was observed that ...”). Remember to check spelling. If your native language is not English, please get a native English-speaking colleague to carefully proofread your paper.

MATH

If you are using *Word,* use either the Microsoft Equation Editor or the *MathType* add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation *or* MathType Equation). “Float over text” should *not* be selected.

*Equations*

Number equations consecutively with equation numbers in parentheses flush with the right margin, as in (1). First use the equation editor to create the equation. Then select the “Equation” markup style. Press the tab key and write the equation number in parentheses. To make your equations more compact, you may use the solidus ( / ), the exp function, or appropriate exponents. Use parentheses to avoid ambiguities in denominators. Punctuate equations when they are part of a sentence, as in

(1)

Be sure that the symbols in your equation have been defined before the equation appears or immediately following. Italicize symbols (*T* might refer to temperature, but T is the unit tesla). Refer to “(1),” not “Eq. (1)” or “equation (1),” except at the beginning of a sentence: “Equation (1) is ... .”

Units

Use either SI (MKS) or CGS as primary units. (SI units are strongly encouraged.) English units may be used as secondary units (in parentheses). This applies to papers in data storage**.** For example, write “15 Gb/cm2 (100 Gb/in2).” An exception is when English units are used as identifiers in trade, such as “3½-in disk drive.” Avoid combining SI and CGS units, such as current in amperes and magnetic field in oersteds. This often leads to confusion because equations do not balance dimensionally. If you must use mixed units, clearly state the units for each quantity in an equation.

The SI unit for magnetic field strength *H* is A/m. However, if you wish to use units of T, either refer to magnetic flux density *B* or magnetic field strength symbolized as µ0*H*. Use the center dot to separate compound units, e.g., “A·m2.”

Some Common Mistakes

The word “data” is plural, not singular. The subscript for the permeability of vacuum µ0 is zero, not a lowercase letter “o.” The term for residual magnetization is “remanence”; the adjective is “remanent”; do not write “remnance” or “remnant.” Use the word “micrometer” instead of “micron.” A graph within a graph is an “inset,” not an “insert.” The word “alternatively” is preferred to the word “alternately” (unless you really mean something that alternates). Use the word “whereas” instead of “while” (unless you are referring to simultaneous events). Do not use the word “essentially” to mean “approximately” or “effectively.” Do not use the word “issue” as a euphemism for “problem.” When compositions are not specified, separate chemical symbols by en-dashes; for example, “NiMn” indicates the intermetallic compound Ni0.5Mn0.5 whereas “Ni–Mn” indicates an alloy of some composition NixMn1-x.

Be aware of the different meanings of the homophones “affect” (usually a verb) and “effect” (usually a noun), “complement” and “compliment,” “discreet” and “discrete,” “principal” (e.g., “principal investigator”) and “principle” (e.g., “principle of measurement”). Do not confuse “imply” and “infer.”

Prefixes such as “non,” “sub,” “micro,” “multi,” and “ultra” are not independent words; they should be joined to the words they modify, usually without a hyphen. There is no period after the “et” in the Latin abbreviation “*et al.*” (it is also italicized). The abbreviation “i.e.,” means “that is,” and the abbreviation “e.g.,” means “for example” (these abbreviations are not italicized).

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Fig. 1. Magnetization as a function of applied field. Note that “Fig.” is abbreviated. There is a period after the figure number, followed by two spaces. It is good practice to explain the significance of the figure in the caption.

TABLE I

Units for Magnetic Properties

|  |  |  |
| --- | --- | --- |
| Symbol | Quantity | Conversion from Gaussian and  CGS EMU to SI a |
| Φ | magnetic flux | 1 Mx → 10−8 Wb = 10−8 V·s |
| *B* | magnetic flux density,  magnetic induction | 1 G → 10−4 T = 10−4 Wb/m2 |
| *H* | magnetic field strength | 1 Oe → 103/(4π) A/m |
| *m* | magnetic moment | 1 erg/G = 1 emu  → 10−3 A·m2 = 10−3 J/T |
| *M* | magnetization | 1 erg/(G·cm3) = 1 emu/cm3  → 103 A/m |
| 4π*M* | magnetization | 1 G → 103/(4π) A/m |
| σ | specific magnetization | 1 erg/(G·g) = 1 emu/g → 1 A·m2/kg |
| *j* | magnetic dipole  moment | 1 erg/G = 1 emu  → 4π × 10−10 Wb·m |
| *J* | magnetic polarization | 1 erg/(G·cm3) = 1 emu/cm3  → 4π × 10−4 T |
| χ*,* κ | susceptibility | 1 → 4π |
| χρ | mass susceptibility | 1 cm3/g → 4π × 10−3 m3/kg |
| μ | permeability | 1 → 4π × 10−7 H/m  = 4π × 10−7 Wb/(A·m) |
| μr | relative permeability | μ → μr |
| *w, W* | energy density | 1 erg/cm3 → 10−1 J/m3 |
| *N, D* | demagnetizing factor | 1 → 1/(4π) |

Vertical lines are optional in tables. Statements that serve as captions for the entire table do not need footnote letters.

aGaussian units are the same as cg emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted; Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.

Guidelines for Graphics Preparation   
and Submission

*Types of Graphics*

The following list outlines the different types of graphics published in IEEE journals. They are categorized based on their construction, and use of color / shades of gray:

*Color/Grayscale figures*

Figures that are meant to appear in color, or shades of black/gray. Such figures may include photographs,   
illustrations, multicolor graphs, and flowcharts.

*Line Art figures*

Figures that are composed of only black lines and shapes. These figures should have no shades or half-tones of gray, only black and white.

*Author photos*

Head and shoulders shots of authors that appear at the end of our papers.

*Tables*Data charts which are typically black and white, but sometimes include color.

*Multipart figures*

Figures compiled of more than one sub-figure presented side-by-side, or stacked. If a multipart figure is made up of multiple figure types (one part is lineart, and another is grayscale or color) the figure should meet the stricter guidelines.

*File Formats For Graphics*

Format and save your graphics using a suitable graphics processing program that will allow you to create the images as PostScript (PS), Encapsulated PostScript (.EPS), Tagged Image File Format (.TIFF), Portable Document Format (.PDF), or Portable Network Graphics (.PNG) sizes them, and adjusts the resolution settings. If you created your source files in one of the following programs you will be able to submit the graphics without converting to a PS, EPS, TIFF, PDF, or PNG file: Microsoft Word, Microsoft PowerPoint, or Microsoft Excel. Though it is not required, it is strongly recommended that these files be saved in PDF format rather than DOC, XLS, or PPT. Doing so will protect your figures from common font and arrow stroke issues that occur when working on the files across multiple platforms. When submitting your final paper, your graphics should all be submitted individually in one of these formats along with the manuscript.

*Sizing of Graphics*

Most charts, graphs, and tables are one column wide (3.5 inches / 88 millimeters / 21 picas) or page wide (7.16 inches / 181 millimeters / 43 picas). The maximum depth a graphic can be is 8.5 inches (216 millimeters / 54 picas). When choosing the depth of a graphic, please allow space for a caption. Figures can be sized between column and page widths if the author chooses, however it is recommended that figures are not sized less than column width unless when necessary.

There is currently one publication with column measurements that do not coincide with those listed above. Proceedings of the IEEE has a column measurement of 3.25 inches (82.5 millimeters / 19.5 picas).

The final printed size of author photographs is exactly   
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*Resolution*

The proper resolution of your figures will depend on the type of figure it is as defined in the “Types of Figures” section. Author photographs, color, and grayscale figures should be at least 300dpi. Line art, including tables should be a minimum of 600dpi.

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In order to preserve the figures’ integrity across multiple computer platforms, we accept files in the following formats: .EPS/.PDF/.PS. All fonts must be embedded or text converted to outlines in order to achieve the best-quality results.

*Color Space*

The term color space refers to the entire sum of colors that can be represented within the said medium. For our purposes, the three main color spaces are Grayscale, RGB (red/green/blue) and CMYK (cyan/magenta/yellow/black). RGB is generally used with on-screen graphics, whereas CMYK is used for printing purposes.

All color figures should be generated in RGB or CMYK color space. Grayscale images should be submitted in Grayscale color space. Line art may be provided in grayscale OR bitmap colorspace. Note that “bitmap colorspace” and “bitmap file format” are not the same thing. When bitmap color space is selected, .TIF/.TIFF/.PNG are the recommended file formats.

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When preparing your graphics IEEE suggests that you use of one of the following Open Type fonts: Times New Roman, Helvetica, Arial, Cambria, and Symbol. If you are supplying EPS, PS, or PDF files all fonts must be embedded. Some fonts may only be native to your operating system; without the fonts embedded, parts of the graphic may be distorted or missing.

A safe option when finalizing your figures is to strip out the fonts before you save the files, creating “outline” type. This converts fonts to artwork what will appear uniformly on any screen.

*Using Labels Within Figures*

*Figure Axis labels*

Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the quantity “Magnetization,” or “Magnetization *M*,” not just “*M*.” Put units in parentheses. Do not label axes only with units. As in Fig. 1, for example, write “Magnetization (A/m)” or “Magnetization (Am−1),” not just “A/m.” Do not label axes with a ratio of quantities and units. For example, write “Temperature (K),” not “Temperature/K.”

Multipliers can be especially confusing. Write “Magnetization (kA/m)” or “Magnetization (103 A/m).” Do not write “Magnetization (A/m) × 1000” because the reader would not know whether the top axis label in Fig. 1 meant 16000 A/m or 0.016 A/m. Figure labels should be legible, approximately 8 to 10 point type.

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Multipart figures should be combined and labeled before final submission. Labels should appear centered below each subfigure in 8 point Times New Roman font in the format of (a) (b) (c).

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E. P. Wigner, “Theory of traveling-wave optical laser,”   
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P. Kopyt *et al., “*Electric properties of graphene-based conductive layers from DC up to terahertz range,” *IEEE THz Sci. Technol.,* to be published. DOI: 10.1109/TTHZ.2016.2544142.

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From 2001 to 2004, he was a Research Assistant with the Princeton Plasma Physics Laboratory. Since 2009, he has been an Assistant Professor with the Mechanical Engineering Department, Texas A&M University, College Station. He is the author of three books, more than 150 articles, and more than 70 inventions. His research interests include high-pressure and high-density nonthermal plasma discharge processes and applications, microscale plasma discharges, discharges in liquids, spectroscopic diagnostics, plasma propulsion, and innovation plasma applications. He is an Associate Editor of the journal *Earth*, *Moon*, *Planets*, and holds two patents.

Dr. Author was a recipient of the International Association of Geomagnetism and Aeronomy Young Scientist Award for Excellence in 2008, and the IEEE Electromagnetic Compatibility Society Best Symposium Paper Award in 2011.

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Mr. Author’s awards and honors include the Frew Fellowship (Australian Academy of Science), the I. I. Rabi Prize (APS), the European Frequency and Time Forum Award, the Carl Zeiss Research Award, the William F. Meggers Award and the Adolph Lomb Medal (OSA).

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