Daniel Minoli • Jo-Anne Dressendofer

High-Density and De-Densified Smart Campus Communications

Technologies, Integration, Implementation, and Applications

WILEY

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In loving memory of my wife Anna (Dan)

Era una santa e completò la sua missione con passione, pur giovane.

"E se dal caro oggetto, Lungi convien che sia, convien che sia, Sospirerò penando, Ogni momento" (from a stanza in Vivaldi's "Vedrò con mio diletto")

In loving memory of my mother Helene (Jo-Anne)

Who was there for every tear along my not-so-easy career and pushed me to dream even bigger

CONTENTS

PREFACE

High-density campus communications have traditionally been important in many environments, including airports, stadiums, convention centers, shopping malls, classrooms, hospitals, cruise ships, train and subway stations, evangelical megachurches, large multiple dwelling units, boardwalks, (special events in) parks, dense smart cities, and other venues. These communications span several domains: people-to-people, people-to-websites, people-to-applications, sensors-to-cloud analytics, and machines-to-machines/device-to-device. While the later Internet of Things (IoT) applications are generally (but not always) low speed, the former applications are typically high speed. In many settings, people access videos (*a la* Over The Top [OTT] mode) or websites and applications that often include short videos or other high data-rate content. Deploying optimally performing high-density campus communication systems is desired and required in many cases, but it can, at the same time, be a complex task to undertake successfully.

High-density campus communications play a role in the evolution of Smart Campuses but also drive the Smart City and Smart Building use cases. Connectivity is now considered a fourth utility (in addition to gas, water, and electricity). In fact, massive-type communication is a recognized requirement of 5G, even if just in the machine-type communication environment. In the campus applications just cited, people-to-people, people-to-websites, and people-to-applications connectivity is increasingly important, given that nearly everyone now carries a smartphone and many apps entail high-throughput transmissions.

There are unique requirements and unique designs required for high-density communications, particularly because of the relative scarcity of available spectrum. In addition, there has been and continues to be a set of transitions, even transformations, of the underlying technologies. The world has moved to IP for all data, voice, and video communications. Additionally, there is a trend toward the use of Wi-Fi-based hotspot communication in all practical situations, due to near ubiquity of service, lower end-user costs, higher bandwidth, technical simplicity, lower infrastructure costs, decentralized administration, regulation relief, and non-bureaucratic delivery of service (without the reliance of large institutional providers). While 5G promises to deliver a set of new capabilities, neither 3G nor 4G displaced Wi-Fi as a common access technology in the office, in the campus, on the street, and in travel. The technologies per se used for high-density communications are not new (perhaps with the exception of 5G), but the requirements, as well as the design and system synthesis, are relatively unique.

As the second decade of the twenty-first century rolled along, however, a new requirement presented itself due to the worldwide pandemic: physical/desk distancing in support of Office Social Distancing (OSD) and Office Dynamic Cluster Monitoring and Analysis (ODCMA). Wireless technologies have been harvested to address and manage these pressing issues. Real-Time Locating Systems (RTLS) have been employed for a number of years to automatically identify and then track the location of objects or people in real-time, within a building, or in other constrained locations are seeing renewed interest and applications. Even if effective vaccines are found and distributed globally, the common opinion is that many (but not all) societal and workplace changes driven by the pandemic may become permanent.

This book assesses the requirements, technologies, designs, solutions, and trends associated with High-Density Communications (HDC). We believe this to be the first book that specifically synthesizes the topic of applied high-density communications. Chapter 1 looks at the functional requirements for high-density communications. Chapter 2 discusses the traditional data/Wi-Fi Internet access, including OTT video. Chapter 3 addresses the traditional voice/cellular design for campus applications, especially the Distributed Antenna System (DAS). Chapter 4 peruses the traditional sensor networks/IoT services approaches. Chapter 5 is the core of this text and examines evolved Wi-Fi hotspot connectivity and related technologies (Wi-Fi 5, Wi-Fi 6, spectrum, IoT, VoWiFi, DASs, microcells issues, 5G versus Wi-Fi issues), as well as intelligent integration of the discrete set of campus/venue networks into a cohesive platform usable in airports, stadiums, convention centers, classrooms, hospitals, and the like.

Chapter 6 starts the discussion on de-densification, using the same kind of technologies discussed in part one of the book; it considers the topic of office social distancing and discusses one of the available technologies. Chapter 7 covers the use of Ultra-Wideband (UWB) technologies. Chapter 8 addresses the office social distancing challenge using Wi-Fi, Bluetooth, and cellular/smartphone methodologies. Chapter 9 provides a use case for HDC systems, and Chapter 10 offers a pragmatic view for some of the economics of broad deployment of HDC.

The book is targeted to networking professionals, technology planners, campus administrators, service providers, equipment vendors, and educators. It is not a research monograph, but rather it aims at integrating the real-world deployment of technologies, strategies, and implementation issues related to delivering an actual working HDC environment in any of the key venues listed above. It is important to note that the composition of this book started in February 2020. While social distancing in the office and public venues was a crucial short-term goal at press time, the business- and public-venue density requirements will likely resurge over time, likely with some yet to be foreseen modifications.

Many books delve extensively on general technologies of all types; however, they fall short in terms of the economics of such technologies, deployment challenges, associated security issues, and most lack tangible case studies. This book addresses these key aspects, based on actual deployment by the team associated with this writing, at a top US airport.

Some portions of this text make use of patent material filed with the United States Patent Office. All inventors cited are implicitly acknowledged for their contribution to this synthesis.

Daniel Minoli
DVI Communications

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Slice Wireless Solutions
30 December 2020

ABOUT THE AUTHORS

DANIEL MINOLI

Mr. Minoli is the principal consultant at DVI Communications. He has published 60 technical telecom and IT books, many are the first in their field (e.g., the first-ever book on VoIP, the first-ever on outsourcing of telecom services, the first-ever book on metro Ethernet, the first-ever book on green networks, the first-ever book on IPv6 security, the first book on public hotspots, and the first book on IPv6 support of IoT, among others); he has also published 340 other papers (the majority of which are peer-reviewed). Many books focus on raw technologies and fail to address Return on Investment (ROI), deployment, security considerations, and to provide case studies; Mr. Minoli's books aim to address these key issues when documenting the applicability of the underlying technologies.

Mr. Minoli started to work on wireless LANs in the late 1970s as part of ARPANet-sponsored R&D and continued wireless work in the form of Geo/Meo satellite transmission, microwave, free space optics, mmWaves/"wireless fiber," cellular, Wi-Fi WLANs, sensor networks, wireless IoT, crowdsensing, 900 MHz SCADA, BMSs, UltraWideband, and 5G. He has written two books on LANs and several long book chapters on WLANs in other books; and, as noted, he has written a book on public hotspots and a book on metroEthernet/VPLS. At press time, over 225 published US patents, as well as 38 US patent applications, cite his work. Additionally, 5917 academic researchers cite his work in their own publications, according to Google Scholar, including 1887 citations of his books on Wireless Sensor Networks, 569 of his books/papers on IoT, 344 of his books on enterprise architectures, 262 of his books on video, and 259 of his books on VoIP. Mr. Minoli is a reviewer for several publishers, including Elsevier, Springer, IEEE, and Wiley. He has taught (adjunct) over 75 college graduate/undergraduate courses at New York University, Stevens Institute of Technology, and Rutgers University. He has been affiliated with Nokia, Ericsson, AT&T, SES, Prudential Securities, Capital One Financial, and AIG, and has been an expert witness/testifying expert in about 20 patent lawsuits. He has undertaken Intellectual Property (IP) work related to patent invalidity, infringement/non-infringement analysis, breach-of-contract, dispute of equipment functionality, and IP portfolio valuation in the area of packet video/IPTV, packet voice/VoIP, networking, imaging (scanned checks), IoT, and wireless. He has provided Court testimony, sustained numerous depositions, and produced numerous Expert Reports, Rebuttal Reports, and Post Grant Review Declarations.

JO-ANNE DRESSENDOFER

Jo-Anne (Josie) Dressendofer is the founder of SliceWiFi. The firm was launched in 2016 to address the rapidly expanding need for fast, reliable Wi-Fi service in permanent and temporary locations. What started as a goal to become the first "Managed Wi-Fi Brand" ended up becoming the first company to compete with the goliath cellular companies, with Wi-Fi and an all-inclusive technology, turning SliceWiFi into a telecommunications company overnight. SliceWiFi initially achieved market recognition in New York City, as one of the leading Wi-Fi providers in the NY metro area, after successfully supporting difficult, densely populated networking environments such as the Javits Center and downtown Brooklyn rebuilding after Hurricane Sandy; NY Fashion Week's many simultaneous event locations; many hackathons with over a thousand users; the Staten Island Ferry during peak travel over the Hudson River; and the parks at Hudson Yards where no fiber was to be had. In 2017, SliceWiFi won *CIO* magazine's category award for "Top Wireless Solution Providers."

Ms. Dressendofer has led a 25-year career in the tech industry, competing aggressively and winning repeatedly against larger, better-financed multi-billion-dollar competitors. Her firms have a record of being more creative with leading-edge technology deployment and networking engineering than all the legacy providers in play. The recent win at BWI Thurgood Marshall Airport (BWI) against major players in the telecommunications industry was transcendent and proof that the SuperNetwork concept (Chapters 9 and 10) is not only a trendsetter but a victory for all women in technology.

ACKNOWLEDGMENTS

In addition to the inventors cited in this work, Mr. Minoli wishes to warmly thank Mr. Benedict Occhiogrosso, President, DVI Communications, for the continued support and input in all the bleeding-edge technologies discussed in this text. DVI Communications, Inc. is a leading and highly respected Information Technology, ICT consultancy, and systems engineering firm with core competencies in IT, ICT, IoT, M2M, wireless, telecom, security, and audiovisual systems. Throughout its 40+ year history, the firm has supported many organizations deploying traditional and emerging technologies, serving both large enterprises and smaller organizations in numerous vertical markets with complex, state-of-the-art systems often working alongside legacy systems, supporting several generations of technology simultaneously.

Ms. Dressendofer wishes to credit and thank the staff of Slice Wireless Solutions, Inc. (SliceWiFi) for the support of this initiative, as described in Chapter 9 and further synthesized in Chapter 10, in the context of designing and deploying a reimagined Thurgood Marshall Airport (BWI) SuperNetwork and the development of WiSNET. The complete redesign and the initial redeployment of the entire BWI Airport terminal-side and some portions of the operations wireless communication infrastructure, amid the COVID-19 pandemic and the span of 12 months, all while maintaining reliable, uninterrupted airport service, was an enormously complex task. Much has been learned at the practical level and is documented in the last two chapters of this book. John Hutzler, COO, and Ed Wright, CTO, have been instrumental in the successful design and completion of this SuperNetwork redeployment mission, even more so as evinced by the relatively small size and the recent debut of SliceWiFi, and this win against the competition backed by billions faced during the RFP process. Without their labor, there would be no SuperNetwork and no chapters to document herewith. Thanks to Cheryl Beck, CMO and Jeffrey Forester, our legal council.

Lastly, to those who were there before SliceWiFi and who without their contribution would never had led down the path of this incredible development. I especially owe that to Morris Williams, Jiamini Erskine, and Ricky Smith of BWI for having the courage to choose a better way not the old way and stay by our side during the tough times, our Nashville investors and investment team, Eddy Wong, my former partner and mentor, Irwin Cohen whose inspiration and endless contacts led me to the incredible support of Jason Zuckerbrod and Jody Westby, and my six nieces who inspired me every day to do more to open doors and make the world a better place for them. Thank you will never be enough for your help in creating a dream this big, against such odds and see it actualized. Dan Minoli you stand alone in genius and my admiration.

1 Background and Functional Requirements for High-Density Communications

This introductory chapter covers two topics: (i) a basic introduction to the underlying technologies and principles that apply to High-Density Communications (HDC), but not high-density specifics, which are covered in the chapters that follow, and (ii) a discussion of the main requirements for HDC in the context of key use cases. Use cases include airports, stadiums, convention centers, classrooms, amusement parks, train and subway stations, large multiple dwelling units, open air special events, and other venues.[1]

As the second decade of the twenty-first century rolled along, however, a new requirement presented itself due to the worldwide pandemic: physical/desk distancing in support of Office Social[2] Distancing (OSD) and Office Dynamic Cluster Monitoring and Analysis (ODCMA). A "de-densification" effort was established at the time. The de-densification effort in the workplace impacts a large number of factors, including network connectivity services and architectures. Propitiously, wireless technologies have been harvested to address and manage these pressing distancing issues. Even if effective vaccines are found and distributed globally, many agree that some of the societal and workplace changes driven by the pandemic may become permanent. One change likely to remain is the increased reliance on Work From Home (WFH) and along with it, are the implications of greater utilization of a global workforce in what might be called Outsourcing 2.0 (with the 1.0 version having taken place in the 1990s and 2000s). However, "the sun will rise again," and in a few years, people-based HDC may yet again become the norm; in the meantime, a large population of Internet of Things (IoT) devices may indeed require HDC support, and during the pandemic, the e-commerce warehouse use case continues to need HDC support. Thus, while "social distancing" was a short-term goal at press time, the business- and public-venue high-density requirements are expected to resurge and/or continue over time. Further discussion of these issues is provided in the latter part of the chapter.

1.1 BACKGROUND

The principal ways people currently communicate (especially when away from home) are via 4G/Long-Term Evolution (LTE) cellular access, for both voice and data, and/or via a public, institutional, or corporate Wi-Fi™ hotspot. In less populated areas and while in motion, cellular access is typically the norm, rather than Wi-Fi access. In large business and commercial

[1]The composition of this book started in February 2020. While "social distancing" was a short-term goal at that juncture, the business and public venue high-density requirements will resurge and/or continue over time.
[2]Some (more properly) use or prefer the term "spatial distancing."

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buildings (e.g. skyscrapers, hospitals, hotels), internal systems known as Distributed Antenna Systems (DASs) may be used to provide better signal quality to cellular users; these systems interoperate with the public cellular network in a number of ways. When stationary, both choices may be available.

Cellular services are offered by carriers using specific carrier-allocated Radio Frequency (RF) spectrum. Relatively high monthly fees are incurred; additionally, there may be both physical and administrative limits to the amount of bandwidth and interval-accumulated throughput. Wi-Fi makes use of bands that are freely allocated; services could be free or could be nearly free based on some account subscription arrangement.

There are plusses and minuses with both technologies: a signal associated with a cellular service such as 4G/LTE reaches longer distances and is often the best choice in sparsely populated areas (assuming the service is available); high-speed mobility is supported and roaming between towers (cellular access points) is seamless; the service is typically provided by well-established carriers that have experience with availability and Quality of Service (QoS) metrics; large portions of the United States are covered, and; the session bandwidth is often guaranteed for the session's duration once the session is established. Conversely, the service costs for 4G/LTE are relatively high and there are limits to the user throughput; there is relatively limited practical competition among carriers; large base-station antennas are needed to cover large geographic areas; the technology is complex; indoor reception of voice and data can be problematic, creating the need for more indoor antennas; and 5G will require smaller (therefore, a larger number of) cells. Wi-Fi is often perceived to be free; the technology is simpler; the hardware and infrastructure are cheaper; it is a consistent technology between the office and the home; there is more competition in the sense that various establishments (e.g. stores, coffee shops, malls, libraries, institutions) make Wi-Fi service available. However, the technology is subject to interference; the distance is limited; roaming does not work across different providers and may not even work for a given provider, even within limited geography; congestion can occur, and; QoS is not guaranteed. Nonetheless, both technologies fill a role, and both technologies are clearly needed.

There are several Wireless Local Area (WLAN) standards that have evolved over time, including Institute of Electrical and Electronics Engineers (IEEE) standards 802.11a, 802.11b, 802.11g, 802.11n, 802.11ac, 802.11ax. The new standards have been developed to accommodate the evolving requirements for higher speeds. Some protocols and wireless routers provide backward compatibility with older Wi-Fi systems. The Wi-Fi Alliance (an industry group) has announced a banding "generation" designation, as follows:

- Wi-Fi 4 is 802.11n, released in 2009
- Wi-Fi 5 is 802.11ac, released in 2014
- Wi-Fi 6 is the new version, also known as 802.11ax (scheduled for release in 2019)

Earlier versions of Wi-Fi have not been officially branded, but one could label the previous generations as follows:

- Wi-Fi 1: 802.11b, released in 1999
- Wi-Fi 2: 802.11a, released in 1999
- Wi-Fi 3: 802.11g, released in 2003

Radio technologies in cellular communications have grown rapidly. They have evolved since the launch of analog cellular systems in the 1980s, starting from the First Generation (1G) in the 1980s, Second Generation (2G) in the 1990s, Third Generation (3G) in the 2000s, and Fourth Generation (4G) in the 2010s (including LTE and variants of LTE). Fifth Generation (5G) access networks, which can also be referred to as New Radio (NR) access networks, are currently being deployed and are expected to address the demand for exponentially increasing data traffic and are expected to handle an extensive range of use cases and requirements. Basic use cases include, among others, Mobile Broadband (MBB) and Machine-Type Communications (MTC), for example, involving IoT devices – Machine-to-Machine (M2M) communication is a specific IoT niche. The IoT refers to the network of physical objects with Internet connectivity (connected devices) and the communication between them; these connected devices and systems collect and exchange data. The IoT has been defined as "the infrastructure of the information society"; it extends Internet connectivity beyond traditional devices such as desktop and laptop computers and smartphones to a range of devices and everyday entities that use embedded technology to communicate and interact with the external environment [1]. Massive Multiple Inputs and Multiple Outputs (MIMO) designs, new multiple access methods, and novel channel coding approaches are being assessed for use in 5G and HDC environments [2–7].

The upcoming 5G access networks may utilize higher frequencies (i.e. > 6 GHz) to support increasing capacity by allocating larger operating channels and bands, although some lower frequencies can also be used. Millimeter wave (mmWave), the band of spectrum between 30 and 300 GHz, have shorter wavelengths that range from 10 to 1 mm. Currently, much of the mmWave spectrum is underutilized; thus, it can be used to facilitate the deployment of new high-speed services. While it is known that mmWave signals experience severe path loss, penetration loss, and fading, the shorter wavelength at mmWave frequencies also allows more antennas to be packed in the same physical dimension, which allows for large-scale spatial multiplexing and highly directional beamforming [8].

Some observers have predicted the "death of Wi-Fi" at various points in the recent past. To quote Mark Twain (as told by his biographer Albert Bigelow Paine), "the report of my death has been grossly exaggerated." Ignoring the ALOHAnet of the late 1960s/early 1970s, wireless LANs started to appear in the late 1980s/early 1990s (e.g. with the WaveLAN system originally designed by NCR Systems Engineering/Wireless Communication and Networking Division, available commercially in 1990 and for several years, some concepts eventually making their way into the 1997 IEEE 802.11 standard[3]). The generic technology has thus been around for 30 years. When (some form of) 3G/4G/LTE was starting to be deployed, some predicted that it would be the death knell of (public hotspot) Wi-Fi, but it did not happen. In fact, many devices developed the capability of transferring connectivity and roaming seamlessly between the local Wi-Fi (corporate, public, residential) and cellular service – some users even use their cellular-based smartphone to create a small local hotspot to support traditional Wi-Fi elements in their environment. Now with 5G on the horizon, some are offering the same (questionable) prediction about the future of Wi-Fi [9]. As is the case with many pairs of technologies, one technology moves ahead, the other lagging; then at some point, the second technology makes a quantum leap forward, and the original one lags; then again, the original technology makes a new advancement and leapfrogs the other technology, and so on. One can apply this idea to cellular and Wi-Fi in terms of speed/throughput as well as cost and end-device capabilities. In broad terms, Wi-Fi generally offers higher data rates and service can be cheaper; however, large-geography coverage and large-geography roaming are more "natural" in the cellular context. Another observation is that 5G will often require small cells, implying both a similarity with a Wi-Fi

[3] Classic WaveLAN (a pre-802.11 protocol) operated in the 900 MHz or 2.4 GHz ISM bands – pursuant to the publication of the IEEE 802.11 standard in 1997 WaveLAN IEEE, supporting the standard was introduced to the market. In WaveLAN, the radio modem section was hidden from the OS, making the WaveLAN card appear to be a typical Ethernet NIC. WaveLAN laid important foundation for the formation of IEEE 802.11 working group and the resultant creation of Wi-Fi. *Wikipedia, WaveLAN, retrieved 27 January 27 2020.*

hotspot and increased infrastructure and deployment cost. 5G is advocated from the perch of higher speeds, higher density, and reliable connectivity; however, it remains to be seen if these features can be achieved on a large scale (i.e. over a large geographic, national, or international geography) and in a cost-effective manner. The global standard could in theory benefit dispersed IoT sensor support, in a smart city setting, for example, but until recently, the cost of the cellular interface for the sensor tended to be fairly expensive (e.g. in the \$20–40 range); thus, the use of other Low Power Wide Area Network (LPWAN) technologies such as LoRa or Sigfox have taken hold. This interface cost must decrease substantially if the use of 5G cellular in IoT applications is to become ubiquitous.

1.2 REQUIREMENTS FOR HIGH-DENSITY COMMUNICATIONS

HDC can be characterized by several (requirement) metrics. Basic metrics include, but are not limited to, user connection density, traffic volume density, experienced data rate, and peak data rate. Many venues require ultra-high connection density and ultra-high traffic volume density; applications that entail M2M and may typically (but not always) require very low end-to-end latency. For example, 5G systems aim at the following key performance indicators: (i) connection density: one million connections per square kilometer; (ii) traffic volume density: tens of Gbps per square kilometer; (iii) user experienced data rate: 0.1–1 Gbps; (iv) peak data rate: tens of Gbps, and; (iv) end-to-end latency: 1–10 ms. See Figure 1.1. In addition, there is a need for scalability: it is one thing to have high density in a small area (say, a classroom), and it is another matter to be able to sustain that over a large venue (for example, a stadium or airport). For this discussion, it is assumed that the mobility speed is not a factor: pedestrian rates (≤10 km/h) are assumed.

One million connections per square kilometer (also definable as 1 connection per m^2) equates to one connection every 10 ft^2 (1 km^2 = 10 763 910 ft^2); this is considerably higher than the connectivity goals in an office environment, where typically one has an allocated space of 130–150 ft^2 per worker, with one or two connections per worker; this is also higher than the connectivity in a classroom (say a 40 × 40 ft locale and 32 students, or one connection every 50 ft^2). Another example could be train cars with 200 users (perhaps not all simultaneously active) in 1000 ft^2, or one connection every 10 ft^2 if only 50% of the passengers are active at any one point in time.

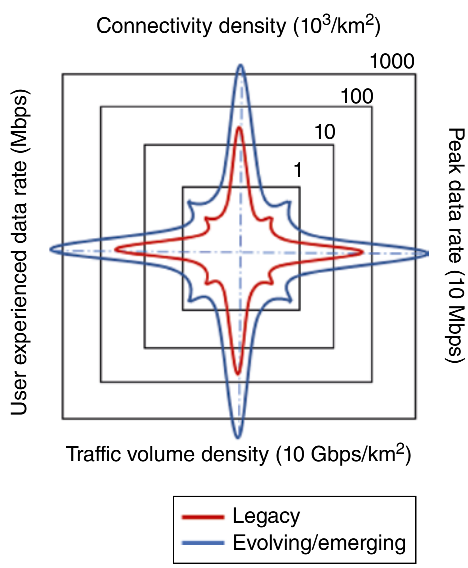

FIGURE 1.1 Requirements bouquet.

TABLE 1.1 Key Performance Indicators HDC Key Performance Indicators (KPIs)

Key Performance Indicators	Description
Connection density	Total number of connected devices per unit area (n/km^2)
User experienced data rate	Minimum data rate for a user in the actual network environment (bps)
Peak data rate	Maximum achievable data rate per user (bps)
Traffic volume density	Total data rate of all users per unit area (bps/km^2)
End-to-end latency	Time lag between the transmission of a data packet from the source and the successful reception at the destination (ms)
Scalability	The ability to retain the above-defined KPIs over large venues and/or geographic areas

In addition to traditional communications, evolving requirements for high-density environments include wearables (for example, in augmented reality applications), M2M, and vehicular traffic in Intelligent Transportation Systems (ITSs) environments. For example, densities of 1 node per m^2 have been identified for augmented reality applications, as with Personal Area Network (PAN) mechanisms [10]. For ITSs, vehicle density has been one of the main metrics used for assessing road traffic conditions: a high vehicle density usually indicates that the road or street is congested [11]; the communication traffic is comprised of beacon signals and user-generated signals. A congested road with stopped vehicular traffic might have, say, 12 cars in an area of 2500 ft^2, or a density of 1 car in about 200 ft^2 – each car could have multiple user sessions. Beyond user counts, the requirements span data rates, as highlighted in Table 1.1; some M2M and process control applications have stringent reliability and latency requirements. Applications such as Ultra HD video Streaming Over The Top (OTT), augmented reality, and online gaming impose challenging requirements on bandwidth and latency; however, these applications are not expected, in the short term at least, to have major deployment in mobile environments, but more so in stationary domiciled environments.

Additional key factors to take into consideration when deploying a state-of-the-art HDC system include spectrum utilization, energy consumption, and infrastructure and endpoint system cost [2]. Spectrum efficiency is measured as the data throughput per unit of spectrum resource per cell or per unit area (bps/Hz/cell or bps/Hz/km^2); energy efficiency is quantified in terms of the number of bits that can be transmitted per unit of energy (bits/J); infrastructure cost efficiency can be defined by the number of bits that can be transmitted per unit cost as computed from network infrastructure amortization/allocation (bits/\$); endpoint system costs are clearly the endsystem costs, especially for the air interface and the protocol stack resources, to support a given maximum throughput; applicable to human devices (e.g. smartphones) and M2M systems. Improvements in these metrics of one-to-two orders of magnitude are being sought compared with legacy environments.

A number of use cases follow.

1.2.1 Pre-pandemic/Long-term Requirements for Airports

Table 1.2 identifies some target design parameters for airport applications, including voice, video, data, IoT, IoT-based security (video surveillance), IoT-based automation, and wayfinding. Two characteristics of airports are as follow: (i) people at the airport are in a "slave" situation typically with nothing to do but to use their electronic devices – this is unlike a stadium or a school where other events and occurrences take up some of the person's time, thus likely diminishing the connection time of the individuals; (ii) multiple automation M2M-like tasks may be at play in the airport including baggage handling, wayfinding/mobility/movement, and security. HDC requirements continue to be active, even, or especially, in emergency cases

TABLE 1.2 HDC KPIs for Airports

Key Performance Indicators	Key Performance Indicators	Pre-pandemic Requirements
Data/VoIP connection density, for people on smartphones, laptops, tablets	Data/VoIP connection density, for people on smartphones, laptops, tablets	1 per 20 ft^2 in terminals
	User experienced data rate	10–50 Mbps
	Peak data rate	100 Mbps
	Traffic volume density	5 Gbps per gate area (200 people per gate)
	End-to-end latency	100 ms
	Wayfinding	Throughout airport and in adjacent spaces, garages, car rental locations
	Area of coverage	Entire airport and in adjacent spaces, garages, car rental locations
Traditional telephony on DAS systems	Dialtone	50 Erlangs per gate area (200 people per gate)
	Call length	10 minutes per call
Connection density, IoT devices	Connection density, IoT devices	1 per 10 ft^2 throughout airport
	User experienced data rate	0.384 Mbps
	Peak data rate	0.768 Mbps
	Traffic volume density	100 Mbps per 1000 ft^2 throughout airport and in adjacent spaces, garages, car rental locations
	End-to-end latency	1–10 ms
	Area of coverage	Entire airport and in adjacent spaces, garages, car rental locations

(these requirements were instituted in early 2020 and continued to be active as of press time [12]) – one example of a challenging airport environment even as the pandemic was already raging, is illustrated in Figure 1.2. Typically, the visitor's public airport communication support is completely separate and walled-off from the high-security airport operations networks – the discussion and network design considered in this book focus on the former and not the latter, although similar technologies may be at play. Another characteristic is that, unlike stadiums, there is a nearly continuous requirement for connectivity, especially in large hub airports; stadiums are only used for relatively short periods a few times a week (once, less than once, or a few times a week). In addition to visitors, there are stationary concession businesses in the airport that would often make use of the same network infrastructure as the public network, although some administratively secure slice (for example, separate Virtual LANs [VLANs] would be used).

According to the National Plan of Integrated Airport Systems (NPIAS), there are approximately 19 700 airports in the United States. 5170 of these airports are open to the general public and 503 of them serve commercial flights. A typical gate area is 30 000 ft^2 (which would equate to an area of 40×75 ft); however, not all of that space is usable for sojourn (implying that some areas within the 30 000 ft^2 area may have a higher concentration of semi-stationary users). If the busy hour concentration of people is 150 people, then there will be 1 person per 200 ft^2 (a 10×20 feet area); however, there may be overcrowding situations where the concentration is comparable to the design goals depicted in Table 1.2. See Table 1.3 for the top 30 airports in the United States. Internationally, the Beijing Capital International Airport (Chaoyang-Shunyi, Beijing,

FIGURE 1.2 A gate area at Fort Lauderdale-Hollywood International Airport is crowded with travelers awaiting Delta flight 1420 to Atlanta Saturday, 14 March 2020. (Courtesy: John Scalzi, Photographer).

China) is the second largest in the world, following the Hartsfield–Jackson Atlanta International Airport, with about 50 million passengers per year as of 2018; Tokyo Haneda Airport (Ōta, Tokyo, Japan) had 41 million passengers; Dubai International Airport (Garhoud, Dubai, United Arab Emirates) had 42 million passengers; and London Heathrow Airport (Hillingdon, London, United Kingdom) had 39 million passengers.

1.2.2 Pre-pandemic/Long-term Requirements for Stadiums

For stadiums, a target of one million connections per square kilometer (also definable as 1 connection per m^2 or one connection every 10 ft^2) has been suggested by some researchers [2]. In the bleachers, the density could be high, even multiple individuals (say 2–3) every 10 ft^2. Requirements include high-capacity data and video access, IoT automation support, which also includes surveillance. The requirements are generally consistent with Table 1.2, with the coverage extending to parking lots. The services span more tightly defined time intervals (as contrasted to airports), possibly giving rise to a challenge in achieving certain goals for the Return on Investment on the infrastructure and the core-network connectivity. The communication session may span the entire sporting event and a specified interval before and after the event.

A football field encompasses 57 600 ft^2 (1.32 acres) but the bleachers may extend the area of coverage to two acres; the parking lots can cover several acres, but the traffic is sparser. Indoor sporting arenas could be smaller. The largest US stadium is the Michigan Stadium in Ann Arbor, Michigan, that seats about 115 000 spectators – about 10 stadiums in the United States can seat over 100 000 people. There are about 90 football stadiums that seat between 50 000 and 99 999 people, and there are about 50 stadiums that seat between 28 500 and 49 999 people. See Table 1.4. There are many other types of sporting venues (e.g. basketball courts, baseball fields, hockey arenas, soccer fields). Soccer field dimensions are somewhat wider than the regulation American football field, being 100–110 m long and 64–73 m wide.

1.2.3 Pre-pandemic/Long-term Requirements for Convention Centers

A target of one million connections per square kilometer (also definable as 1 connection per m^2 or 1 connection every 10 ft^2) appears appropriate. The KPI are comparable to those of Table 1.2 for both people and M2M/IoT functionality. Connectivity is to be supported for both the booth exhibitors (which sometimes can be rather complex) as well as the visiting public. Often there

TABLE 1.3 Top US Airports – Actual and Heuristic Data Shown

Rank (2018)	Airports (Large Hubs)	Major City Served, State	2018 Passengers (in M) (Approx.)	Ave Daily (365 days)	Busy Hour (0.05,0.1,0.2,0.1,0.2,0.1,0.2,0.05)	Gates	Ave People per Gate at BH
1	Hartsfield–Jackson Atlanta International Airport	Atlanta, GA	52	142 100	28 420	192	148
2	Los Angeles International Airport	Los Angeles, CA	43	116 786	23 357	128	182
3	O'Hare International Airport	Chicago, IL	40	109 246	21 849	191	114
4	Dallas/Fort Worth International Airport	Dallas, TX	33	89 865	17 973	182	99
5	Denver International Airport	Denver, CO	31	85 928	17 186	111	155
6	John F. Kennedy International Airport	New York, NY	31	83 675	16 735	128	131
7	San Francisco International Airport	San Francisco, CA	28	76 148	15 230	115	132
8	Seattle–Tacoma International Airport	Seattle, WA	25	68 204	13 641		
9	McCarran International Airport	Las Vegas, NV	24	64 809	12 962		
10	Orlando International Airport	Orlando, FL	23	63 520	12 704		
11	Newark Liberty International Airport	Newark/New York, NJ	23	62 461	12 492		
12	Charlotte Douglas International Airport	Charlotte, NC	22	61 051	12 210		
13	Phoenix Sky Harbor International Airport	Phoenix, AZ	22	59 243	11 849		
14	George Bush Intercontinental Airport	Houston, TX	21	57 967	11 593		
15	Miami International Airport	Miami, FL	21	57 603	11 521		
16	Logan International Airport	Boston, MA	20	54 823	10 965		
17	Minneapolis–Saint Paul International Airport	Minneapolis/St. Paul, MN	18	50 311	10 062		
18	Fort Lauderdale–Hollywood International Airport	Fort Lauderdale, FL	17	48 257	9651		
19	Detroit Metropolitan Airport	Detroit, MI	17	47 775	9555		
20	Philadelphia International Airport	Philadelphia, PA	15	41 879	8376		

21	LaGuardia Airport	New York, NY	15	41 259	8252		
22	Baltimore–Washington International Airport[a]	Baltimore/ Washington, MD	13.373	36 640	7328	75	98
23	Salt Lake City International Airport	Salt Lake City, UT	12	33 503	6701		
24	San Diego International Airport	San Diego, CA	12	33 360	6672		
25	Dulles International Airport	Washington, DC, VA	12	31 858	6372		
26	Reagan National Airport	Washington, DC, VA	11	31 143	6229		
27	Midway International Airport	Chicago, IL	11	29 276	5855		
28	Tampa International Airport	Tampa, FL	10	28 410	5682		
29	Portland International Airport	Portland, OR	10	26 864	5373		
30	Daniel K. Inouye International Airport	Honolulu, HI	9	26 242	5248		

Note: during 2020, most airports in the United States experienced a 60% drop in passengers. Travel was expected to improve during the second half of 2021 and beyond.

[a] *Size:* 3596.3 acres. Passenger Terminal: 2.423 million ft^2; 5 concourses (4 domestic, 1 international/swing); 73 jet gates, 2 gates dedicated to commuter aircraft; square footage per gate: 32 306 ft^2.

TABLE 1.4 Largest US Football Stadiums

Rank	Stadium	Seating Capacity	Location
1	Michigan Stadium	115 000	Ann Arbor, Michigan
2	Beaver Stadium	111 000	University Park, Pennsylvania
3	Kyle Field	111 000	College Station, Texas
4	Ohio Stadium	110 000	Columbus, Ohio
5	Neyland Stadium	109 000	Knoxville, Tennessee
6	Rose Bowl	107 000	Pasadena, California
7	AT&T Stadium	105 000	Arlington, Texas
8	Darrell K Royal–Texas Memorial Stadium	104 000	Austin, Texas
9	Tiger Stadium	102 000	Baton Rouge, Louisiana
10	Bryant–Denny Stadium	102 000	Tuscaloosa, Alabama

TABLE 1.5 Top Convention Centers in the United States

Center	Location	Exhibition Space, Approx. (ft^2)	Total Space, Approx. (ft^2)
McCormick Place	Chicago, Illinois	2 700 000	9 000 000
Orange County Convention Center	Orlando, Florida	2,100 000	7 000 000
Georgia World Congress Center (GWCC)	Atlanta, Georgia	1 500 000	4 000 000
Las Vegas Convention Center	Las Vegas, Nevada	2,200 000	3,200 000
New Orleans Morial Convention Center	New Orleans, Louisiana	1,100 000	3,100 000
America's Center	St. Louis, Missouri	500 000	2 700 000
San Diego Convention Center	San Diego, California	600 000	2,600 000
TCF/Cobo Center	Detroit, Michigan	720 000	2 400 000
Walter E. Washington Convention Center	Washington, DC	700 000	2 300 000
Sands Expo and Convention Center	Las Vegas, Nevada	940 000	2 300 000

is also a video broadcasting function among specialized media outlets that may need to be supported. Since visitors are engaged with the goings-on in the exhibit, the connectivity requirements may be somewhat diffused during those time slots. Connectivity may coincide with extended business hours.

Some events comprise both a set of lecture sessions and exhibit sessions. When lecture sessions are underway, the connectivity requirements (specifically, the traffic volume density) may be low or lower; however, when the sessions wrap up, there may be a pulse-shaped traffic requirement where a large number of participants all want to make phone calls or access the Internet.

There are about 310 convention centers in the United States of various sizes, 50 of which have more than 200 000 ft^2 of total space. See Table 1.5 for the top 10 convention centers in the United States. For example, the largest US convention center is the McCormick Place in Chicago, Illinois, with 9 million ft^2 of space and 2.7 million ft^2 of exhibition space. The exhibit space generally tends to be one-half to one-third of the total space.

1.2.4 Pre-pandemic/Long-term Requirements for Open Air Gatherings and Amusement Parks

Networks for public parks are typically designed around public safety and the availability of cellular service; first responder access is important (e.g. in the context of E911). For data and multimedia services, users will typically utilize their smartphones and 4G/LTE cellular

TABLE 1.6 Top Amusement Parks in the United States

Site	2017 Visitors
1. Magic Kingdom, Lake Buena Vista, Florida	20 450 000
2. Disneyland, California	18 300 000
3. Disney's Animal Kingdom, Florida	12,500 000
4. Epcot, Florida	12,200 000
5. Disney's Hollywood Studios, Florida	10 722 000
6. Universal Studios, Florida	10 198 000
7. Disney California Adventure	9 574 000
8. Universal's Islands of Adventure, Florida	9 549 000
9. Universal Studios, Hollywood	9 056 000
10. Knott's Berry Farm, California	4 034 000

connections; however, in some instances, Wi-Fi is available, as in the latter case, and is employed to move users toward food and merchandize concessions, or for geo-fencing applications. A target of one million connections per square kilometer (also definable as 1 connection per m^2 or 1 connection every 10 ft^2) has been suggested by some researchers [2]. Open air gathering tends to be more "pop up" operations with short-lived operational timeframes; however, the density could be high, even multiple individuals (say 2–3) every 10 ft^2. Requirements include high-capacity data and video access, and perhaps video surveillance.

A lower target seems appropriate for amusement parks, given that people go to these parks (usually with high entrance fees) for entertainment and less for spending time on personal communication devices. There are about 430 parks and amusement parks in the United States; Table 1.6 identifies the 10 top parks.

1.2.5 Pre-pandemic/Long-term Requirements for Classrooms

Classrooms are in session only for certain hours of the day, of the week, of the seasons. Students may toggle between being online and listening to the teachers. In broad terms, a classroom (say of 40×40 ft and 32 students) would require one connection every 50 ft^2.

There were 132 853 K-12 schools in the United States in 2015, according to data from the National Center for Education Statistics (NCES). The average public school size is as follows: city: 591 students; suburban: 656 students; and rural: 358 students. Table 1.7 depicts the enrolment in the top 10 districts in the United States.

TABLE 1.7 Enrolments at Largest US Districts

Rank	District Name	State	Enrollment (K)
1	New York City	NY	1100
2	Los Angeles Unified	CA	634
3	Chicago	IL	378
4	Miami-Dade County	FL	357
5	Clark County	NV	327
6	Broward County	FL	272
7	Houston	TX	216
8	Hillsborough County	FL	214
9	Orange County	FL	200
10	Palm Beach County	FL	193

TABLE 1.8 Example of School Demographics (NYC)

Size Category	Number of Classrooms	Number of Offices	Total Building Area (ft^2)	Approximate Number of Sites
Small	50	10	100 000	250
Medium	100	15	175 000	650
Large	140	25	300 000	275
Campus	200	40	450 000	100
				1275

A school may have a large number of classrooms, in addition to administrative offices. For example, New York City's Department of Education (DOE) is the largest school system in the United States, serving over 1.1 million children across 1800 schools with 140 000+ employees at 1300+ school buildings and 29 administrative sites across New York City. Many sites have multiple schools or administrative offices per building. While individual schools vary greatly in size, a standard set of LAN/WAN equipment, including switches, routers, servers, firewalls, and access points is deployed throughout individual school organizations and shared spaces. These networks provide e-mail, administrative and instructional applications for both wired and wireless devices. Additionally, administrative networks are typically wired and are kept in separate VLANs from instructional networks. Table 1.8 illustrates the approximate size and demographics for New York City DOE School buildings.

In addition to content traffic, there is an increasing need to provide IoT-based functionality such as bathroom sensors for smoking or vaping of substances, Heating, Ventilation, and Air Conditioning (HVAC) operations, and video surveillance.

1.2.6 Pre-pandemic/Long-term Requirements for Train and Subway Stations

While some quote a figure of 6 persons per km^2 in subway stations [2], it is our pragmatic observation that the densities at rush hour are more in line with the parameters of Table 1.2, with concentration of 1 per 10 ft^2 or 1 per 20 ft^2. Table 1.9 provides some information on the subway and rapid transit systems in the United States (about 15 systems in total).

1.2.7 Pre-pandemic/Long-term Requirements for Dense Office Environments

Office space represents a major environment where work is accomplished in the United States and around the world. Data from the Commercial Buildings Energy Consumption Survey indicates that there were 5.6 million commercial buildings in the United States in 2012 (the most

TABLE 1.9 Top Subway and Rapid Transit Systems in the United States

System	Annual Ridership (2018) (M)	Avg. Weekday Ridership (K)	Stations (Approx.)
1. New York City Subway	2629	8765	470
2. Washington Metro	226	764	90
3. Chicago "L"	226	720	145
4. MBTA, Boston	156	510	50
5. BART, Bay Area Rapid Transit	126	417	46
6. SEPTA Philadelphia	94	328	75
7. PATH NJ/NY	92	310	13
8. MARTA, Atlanta	65	206	38