



CRA Insights: The Economics of 5G

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To open or not to open a technological system: insights from the history of mobile phones and their application to 5G*

Is it a good business strategy for a creator of new technology to make that technology available to other companies in the industry, including its competitors? And if so, on what terms? Further, is it a good business strategy for a developer of new technology to allow third-party companies to develop applications for it? And if so, on what terms? These questions go to the core of what it means for a technological system to be “open” or “closed.”

In the history of mobile phones, the first question—whether the creators of new technology are better off allowing other companies in the industry to have access to their intellectual property and, if so, on what terms—has generated controversies since the 1980s, when the Global System for Mobile Communication (GSM) second-generation cellular standard was being developed. Companies that created the technology underlying the GSM standard were reluctant to license their standard-essential intellectual property for free to users of the technology (the cellular carriers). This was especially true of Motorola, which reportedly held about 50% of the GSM standard-essential patents. In an attempt to resolve the problem, the European Telecommunications Standards Institute (ETSI), which was in charge of developing the GSM standard, introduced a policy that set the foundation for the licensing of standard-essential patents under “fair, reasonable, and non-discriminating terms.”¹ The true meaning of this (so-called FRAND) terminology has been litigated often since it was introduced.

The second question—whether the developers of a new technological system are better off allowing third-party companies to develop and commercialize applications for the system and, if so, on what terms—has generated plenty of litigation as well. A recent example is *Epic Games v. Apple Inc.* Epic Games is a technology company that specializes in video games. It is the maker of a popular video game, Fortnite, for iPhone and Android smartphones. The event that triggered the litigation between Epic and Apple happened on August 13, 2020. On that day, Epic updated Fortnite with a new feature that allowed users to pay Epic directly for in-app purchases. With this change, Epic intended to eliminate the intermediary, Apple’s App Store, and thus to avoid paying Apple the traditional 30% fee. In response, Apple removed Fortnite from the App Store the next

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day. The change Epic made to Fortnite also affected the Android version of the game, and Google removed the app from the Google Play Store.²

Leaving aside the question whether closing a standard to other firms in the industry constitutes unfair competition, the question remains whether it is a sound business strategy. In this *Insights*, we examine open and closed standards in the history of mobile phones, a technology for which the issue will continue to play a prominent role as the wireless industry transitions to 5G. We develop two case studies and explore the trade-offs associated with the decision to open a standard.

Background

Mobile phones are system-type products: they are made up of multiple components that interact with one another.³ For example, smartphones have a hardware and a software layer. Mobile-phone software includes an operating system and a variety of applications that make the device useful for purposes other than voice communications. In addition, cellular systems include not just handheld devices but also base stations that send signals to, and receive signals from, the devices we carry around every day.

For a system to function properly, the system's components need to interact smoothly with each other. This is as true for the hardware and software layers on a modern smartphone as it is for a mobile operating system and the applications created for it. Of the many interfaces that define a cellular system, the so-called air interface is particularly important because it defines how handheld devices interact with the system's base stations. Starting in the 1980s, each generation of mobile phones has had one or more air-interface standards.⁴

At some point in the history of a system (or standard), its "owner" or "sponsor" faces the decision whether to "open" it or not. The owner of a completely closed standard excludes outsiders through patents, copyright, secrecy, and other means.⁵ By contrast, the specifications of a fully open technological system are neither owned nor controlled by any entity and are thus accessible to all.⁶ There are degrees of openness, of course. A system may rely on intellectual property that is not available free, but if the owners of the intellectual property license it in exchange for reasonable royalties, they open the system to many industry participants interested in using the technology.

The two main trade-offs associated with the decision to open a technological system are: diffusion versus appropriability and diversity versus control.⁷ Opening a system usually encourages diffusion by, for example, eliminating consumers' fears of being locked in to a single vendor.⁸ Opening a system also facilitates diffusion by making it easier for third-party developers to create applications for the standard. At the same time, opening a system may make it more difficult for the owner or sponsor to appropriate the financial returns the system generates.

The trade-off between diversity and control arises when a technology or standard requires continuous innovation. Opening a system makes it easier for companies other than the owner or sponsor to improve the system through innovation.⁹ At the same time, however, when many parties try to innovate simultaneously, the coherence of the system may be lost: too much diversity may lead to fragmentation of the standard, which in turn may conspire against further diffusion.¹⁰ By contrast, the owner of a closed standard retains full control over the evolution of the system.

Open versus closed standards in first-generation cellular phones

Our first case study of the trade-offs involved in opening a system or standard focuses on first-generation cellular phones. In 1978, there was just one cellular-phone system in the world—a trial network established by Illinois Bell in the Chicago area that was designed to serve no more than 2,500 users.¹¹ Ten years later, by the end of 1988, 45 countries had installed at least one cellular system, and these systems, combined, were serving more than four million cellular subscribers around the world.¹² The cellular revolution had begun.

The countries that installed the first cellular systems beginning in the late 1970s were of two types: some created their own air-interface standard, while others imported a standard developed somewhere else. Most of the countries that installed cellular systems in the 1980s were standard importers rather than standard creators. Table 1 presents a timeline of the worldwide adoption of cellular systems between 1979 and 1989. All these systems belonged to what is known as the “first generation” (or analog generation) of cellular networks.

Table 1: Timeline of early cellular systems, 1979–1989

Year	Africa	Asia	Europe	The Americas	Oceania
1979		Japan			
1980					
1981		Saudi Arabia	Norway, Sweden		
1982			Denmark, Finland, Spain		
1983				United States	
1984		Hong Kong, Korea	Austria	Canada	
1985	Tunisia	Malaysia, Oman	Ireland, Italy, Luxembourg, Netherlands, Britain, West Germany, France		
1986	South Africa	Israel, Thailand, Indonesia	Iceland, Turkey	Virgin Islands	Australia
1987	Morocco	Bahrain, Singapore	Belgium, Switzerland	Cayman Islands, Dominican Republic, Bermuda	New Zealand
1988	Zaire	China, Macau	Cyprus	Venezuela	
1989	Algeria, Mauritania	Brunei, Taiwan, Sri Lanka, UAE	Greece, Malta, Portugal	Argentina, Chile, Curacao, Antigua, St. Kitts, Mexico, Dutch Antilles	

Sources: elaborated by the authors on the basis of information in U.S. Department of Commerce, *A Competitive Assessment of the U.S. Radiotelephone Industry* (Washington DC: U.S. Department of Commerce, 1988), p. 76; J. Funk, *Global competition between and within standards* (Houndmills and New York: Palgrave, 2002), p. 43; and G. Garrard, *Cellular Communications: Worldwide Market Development* (Boston and London: Artech House, 1998)

During the first generation of cellular systems, there were two waves of standard creators. The first wave included Japan, the United States, and the Scandinavian countries, which introduced their first cellular networks between 1979 and 1983. The second wave included the UK, Italy, France, and Germany, all of which set up their first systems in 1985.¹³ In both waves, countries faced the decision to make their cellular standards open or closed, and some chose the former and others the latter. This choice shaped the extent to which first-generation cellular standards were adopted (both in the countries that created them and elsewhere).

Among the countries that belonged to the first wave of standards creators, Japan developed a closed standard, the so-called NTT high-capacity system, while the United States and Scandinavia created open standards—AMPS and NMT, respectively.¹⁴ In the second wave of first-generation standard creators, Germany, Italy, and France developed closed standards—Netz-C, RTMS, and Radiocom 2000, respectively—while the UK created TACS, an open standard inspired by the American standard AMPS.¹⁵

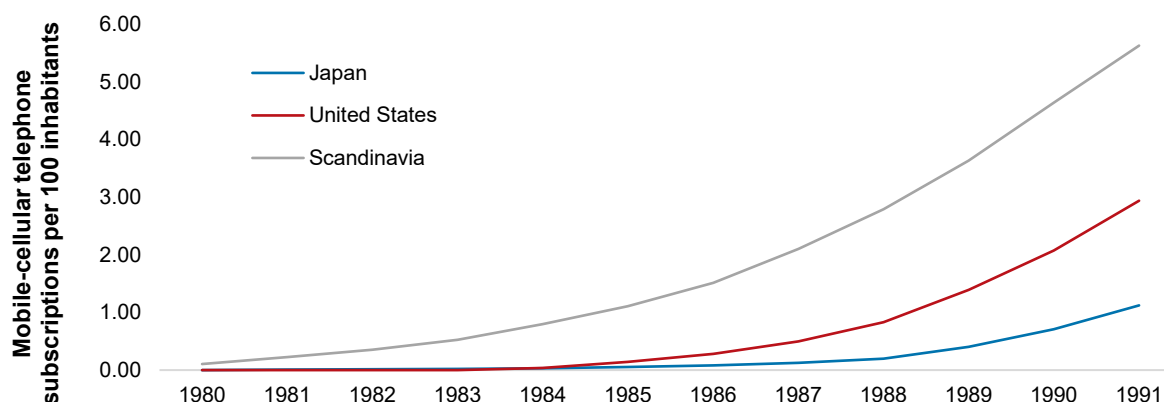
The countries that adopted closed standards—Japan, Germany, Italy, and France—had several things in common. First, in each country the standard was developed by the domestic Post, Telegraph, and Telecommunications (PTT) administration in collaboration with a powerful local electronics supplier (or group of suppliers). Second, the standard was incompatible with all cellular systems outside the country. Third, the local electronics and telecommunications conglomerates that participated in the creation of the standard—Siemens in Germany, Italtel in Italy, Matra in France, and a combination of NEC, Fujitsu, and Mitsubishi in Japan—were the only suppliers of infrastructure and devices for the standard, at least in the early years. Finally, the creation of the cellular standard was viewed as an opportunity to do industrial policy—that is, as a way to help the local electronics suppliers develop cellular technology and know-how.

By contrast, the standards developed in the United States, Scandinavia, and the UK were open: the specifications were made available to all comers, which facilitated competition among infrastructure and device manufacturers within the standard.¹⁶ In the US market, for example, the largest cellular market in the world during the 1980s, competition among handset manufacturers was intense and involved companies from the United States (Motorola), Europe (Nokia and Ericsson), and Japan (Toshiba and Mitsubishi).

Standards that were open were quickly disseminated in the marketplace for two reasons. First, competition among infrastructure manufacturers lowered the price that carriers paid for cellular equipment, such as base stations and switching systems. More importantly, competition among handset manufacturers lowered the price of phones, which made it easier for users to gain access to cellular services. Second, because of network effects, early adoption fostered further adoption.¹⁷

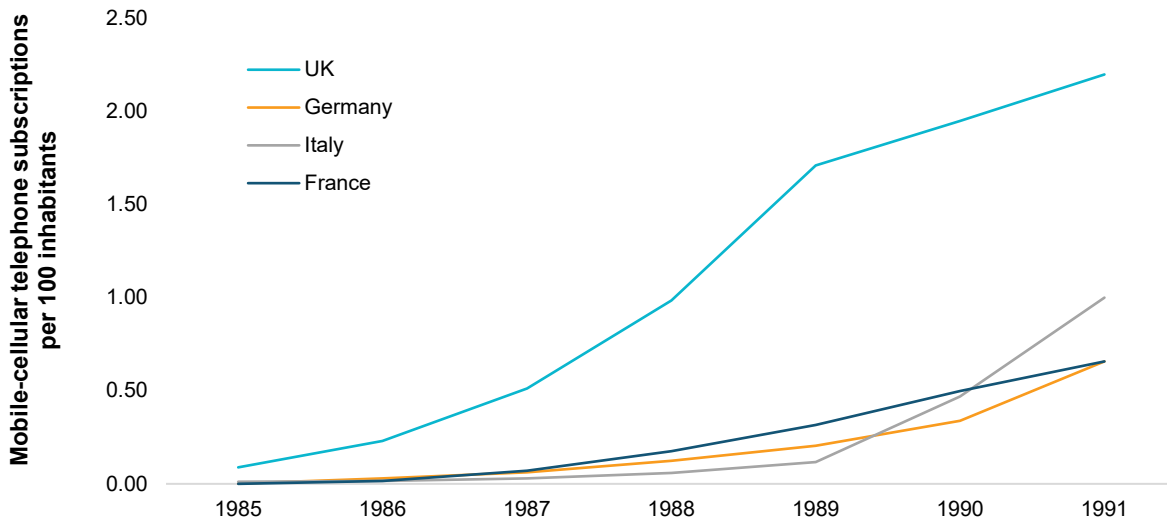
Figure 1 tracks the evolution of cellular density among first-wave standard creators (Japan, Scandinavia, and the United States). Figure 2 presents the same information for the second wave of standard creators (Italy, Germany, France, and the UK).

Figure 1: Mobile-cellular Telephone Subscriptions per 100 Inhabitants among First-Wave Standard Creators, 1980–1991



Note: Scandinavia includes Finland, Norway, Sweden, and Denmark.
Source: ITU Data

Figure 2: Mobile-cellular Telephone Subscriptions per 100 Inhabitants among Second-Wave Standard Creators, 1985–1991



Source: ITU Data

Figures 1 and 2 show that, in each wave, cellular-phone subscriptions grew faster (relative to population) in the country (or countries) that adopted open standards than in those that chose closed standards. In the first wave, Scandinavia and the United States beat Japan. In the second, the UK beat all others.

Open standards were more heavily adopted not only in the countries where they were created but elsewhere as well. Table 2 tracks the worldwide adoption of all first-generation cellular standards (with countries grouped by standard).

Table 2 shows that the AMPS, NMT, and TACS standards were heavily adopted outside the countries where they were developed. By contrast, and with minor exceptions, the Japanese, German, French, and Italian first-generation standards were adopted only in the countries that created them.

Table 2: Standard creators and importers in the 1980s

Standard	1981	1982	1983	1984	1985	1986	1987	1988	1989
NMT	<i>Sweden</i>	<i>Denmark</i>		<i>Austria</i>	<i>Luxembourg</i>	<i>Iceland</i>	<i>Belgium</i>	<i>Cyprus</i>	<i>France</i>
	<i>Norway</i>	<i>Finland</i>			<i>Netherlands</i>	<i>Turkey</i>	<i>Morocco</i>		<i>Algeria</i>
	<i>S. Arabia</i>	<i>Spain</i>			<i>Oman</i>	<i>Thailand</i>	<i>Switzerland</i>		<i>Cambodia</i>
					<i>Tunisia</i>	<i>Indonesia</i>			<i>Faroe Islands</i>
					<i>Malaysia</i>				
AMPS			<i>US</i>	<i>Canada</i>		<i>Australia</i>	<i>Cayman</i>	<i>Venezuela</i>	<i>Chile</i>
				<i>South Korea</i>		<i>Virgin Islands</i>	<i>Bermuda</i>	<i>Zaire</i>	<i>Curaçao</i>
						<i>Israel</i>	<i>Dom. Republic</i>		<i>Argentina</i>
							<i>Singapore</i>		<i>Antigua</i>
							<i>New Zealand</i>		<i>St. Kitts</i>
							<i>Thailand</i>		<i>Mexico</i>
							<i>Bahrain</i>		<i>Dutch Antilles</i>
									<i>Brunei</i>
TACS				<i>Hong Kong</i>	<i>Ireland</i>			<i>Macao</i>	<i>Sri Lanka</i>
					<i>Britain</i>			<i>China</i>	<i>Japan</i>
									<i>Malaysia</i>
									<i>Taiwan</i>
									<i>Mauritania</i>
Other	<i>Japan (1979)</i>				<i>Germany</i>	<i>South Africa</i>			<i>Portugal</i>
					<i>France</i>				
					<i>Italy</i>				

*Standard creators are in italics

Source: J. Funk, *Global competition between and within standards* (New York: Palgrave, 2002), p. 43

Did factors other than the open nature of their standards facilitate rapid growth in cellular-phone subscriptions in countries such as the United States and the UK? These countries were peculiar among cellular adopters in the 1980s because they introduced competition in cellular network services—more than one cellular carrier—from the very beginning, while most other countries had monopolistic network-services markets. Specifically, the United States had a collection of regional duopolies and the UK had a national duopoly during the 1980s. The literature has shown, however, that duopolistic network-services markets during the 1980s did not lead to a substantial decline in subscription tariffs—in the UK, for example, subscription fees remained constant in nominal terms until the early 1990s.¹⁸ The evidence suggests that during the 1980s, within-standard competition among cellular-technology suppliers in the context of open standards mattered more for adoption than within-standard competition among cellular carriers.

Open versus closed standards in smartphones

Our second case study of the costs and benefits of opening a technological system focuses on smartphones. The mobile phones used in the 1980s were heavy, primitive contraptions that allowed users to make voice calls and not much else. In fact, many of them were not even handheld devices: they were rather large pieces of equipment designed to be installed and used in vehicles.¹⁹

Mobile-phone technology evolved dramatically between the 1980s and the 2000s. Semiconductors became increasingly smaller and more powerful, and improvements in semiconductor technology facilitated the rise of what today we call smartphones.²⁰ By the early 2000s, a variety of smartphones were available on the market. The main competitors at the time were Research in Motion, Palm, Microsoft, and Symbian.²¹ During the 2000s, Symbian became the leading smartphone operating system in the world in units sold, while BlackBerry dominated the US market.

The late 2000s witnessed the arrival of two new smartphone operating systems that radically altered the cellular world: iOS, designed by Apple and embedded in the iPhone, and Android, supplied by Google and embedded in many smartphones manufactured by Google's hardware partners.²² Apple introduced the first version of its iPhone in June 2007. T-Mobile released the first smartphone running on Android, the HTC Dream, in September 2008. When the iPhone was introduced, the Symbian operating system accounted for 66% of all smartphone units sold in the world. The share of the iPhone OS in global shipments of smartphone operating systems grew quickly to about 16% in the fourth quarter of 2009.²³

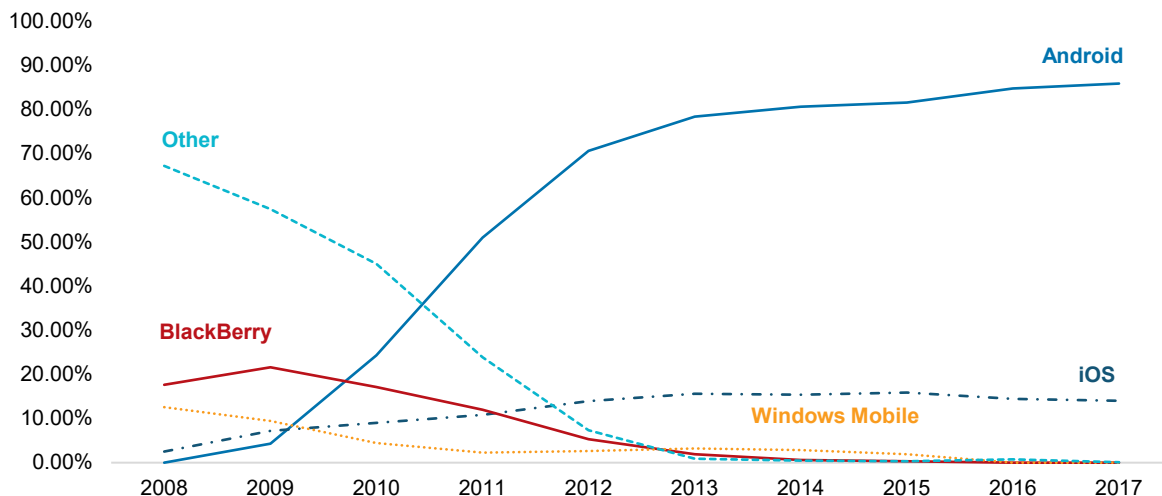
Behind the marketing hoopla surrounding the introduction of the iPhone and the first Android smartphones, the competition between iOS and Android revived the debate about the virtues and weaknesses of open versus closed technological systems. The iPhone was, in essence, a closed system, a proprietary bundle of hardware and software marketed exclusively by its owner. By contrast, Android was an open system. Unlike Apple, which chose not to license the intellectual property at the core of the iPhone, Google supplied an operating system and licensed it to any and all handset makers. Further, Google open-sourced the Android mobile operating system and made it available free of royalties.

In fact, Google went one step further in opening the system: it not only licensed Android to all comers without charge, it also got its partners involved in the development of the Android operating system. In November 2007, only a few months after the iPhone reached the market, a group of technology companies that included Google, T-Mobile, HTC, Qualcomm, and Motorola announced that they would form the Open Handset Alliance to develop the Android operating system.²⁴

After intense internal debates, Apple decided not to keep its iPhone system completely closed. When it introduced its iPhone 3G in mid-2008, it also introduced a digital distribution platform—the App Store—featuring third-party applications for both the iPhone and the iPod music player. By early September 2008, over 3,000 apps were available in the App Store, and users had already made more than 100 million app downloads.²⁵ In October 2008, Google responded with its own app store, Android Market (later renamed Google Play). But leaving aside third-party apps, which were available both for the iPhone and for Android smartphones, the contrast between the iPhone and Android devices was stark—the iPhone was a closed system owned by Apple and not licensed to anybody, whereas Android was an open-source platform co-developed by Google and its partners and licensed free to all comers.

How did the contrast between open and closed systems play out in the world smartphone market? In terms of diffusion, the open system clearly beat the closed system. After the introduction of the iPhone in mid-2007, iOS's share in global shipments of smartphone operating systems grew quickly. Its growth, however, was soon slowed by the rise of Android smartphones. Figure 3 tracks the evolution of smartphone shipments between 2008 and 2017.

Figure 3: Global shares of smartphone operating systems, units sold, 2008–2017



Source: Gartner Press Releases

Figure 3 shows that, by 2017, Android was the leading mobile operating system in the world with a share of more than 80% of all units sold, and Apple's iOS was its only competitor (with a share that was about a quarter the size of Android's). One of the reasons Android was more widely adopted was that the open nature of the standard generated competition within the standard: device makers introduced a wide array of Android smartphones with a broad range of prices, which facilitated adoption, especially in emergent markets.

But openness also brought its problems for Android. With Google and its partners all innovating at the same time, eventually some of the coherence of the system was lost. New versions of the operating system were released often, sometimes just a few months apart from one another, and handset makers tended to modify the interface to achieve some degree of product differentiation. This led to the coexistence of many flavors of Android, which sometimes led to consumer and developer confusion.²⁶ While Apple retained full control over the evolution of the iPhone technological system, Google had to give up some control in order to achieve partner collaboration and widespread diffusion.

In addition, it was easier for Apple to appropriate the returns from a closed technological system such as the iPhone than it was for Google to profit from an open operating system such as Android. In early 2016, for example, in the midst of protracted litigation with Google, Oracle estimated that Google had generated \$31 billion in revenues and \$22 billion in profits from Android since 2008.²⁷ Since Google had never charged for Android, the revenues and profits in question likely came from two sources: ads played on Android phones and fees charged to developers that sold apps in the Android Market.²⁸ Although these are large revenue and profit figures, they do not compare with the returns Apple has reaped from the iPhone: as of mid-2017, Apple had generated \$738 billion in revenues and \$100 billion in profits from iPhone sales.²⁹ The contrast is even starker if one keeps in mind that Apple had sold about 1.2 billion phones by late 2017, whereas Google's handset partners had sold about 6.3 billion Android phones. Other sources argue that Apple's profit margins on the iPhone have historically been higher than 50%, which suggests that the iPhone may have generated profits well above \$100 billion since its inception.³⁰

It could be argued that comparing revenues and profits for Android and the iPhone is unjustified, since Android is a mobile operating system and the iPhone is a bundle of hardware and software. But even taking the hardware side of the Android ecosystem into account, Apple still seems to

have come out ahead in appropriating the returns from its smartphone system. This is so because appropriating the returns from Android co-innovation has been difficult for Android licensees. They have faced the same problem that the “IBM clones”—the makers of personal computers that licensed the Microsoft operating systems and Intel chips—faced in the 1980s: hardware tends to become commoditized. The Android device makers have faced a catch-22: too much differentiation in software leads to fragmentation of the Android standard, but without enough differentiation, hardware becomes a commodity and profits decline.³¹

Conclusion

As the cellular industry transitions to 5G, discussions about the appeal of open versus closed solutions are becoming more intense. In recent years, industry stakeholders—including carriers and infrastructure suppliers—have debated the virtues and weaknesses of open versus closed approaches to the definition of radio access network (RAN) interfaces.³² RAN interfaces handle the reception and transmission of wireless signals between devices and the main network. The debate between “closed” RAN and “open” RAN is between those who advocate the use of traditional, proprietary pieces of network hardware and those who prefer to replace such hardware with software running on general-purpose computers, as discussed in an earlier [Insights](#). The historical case studies analyzed in this *Insights* suggest that decisions made in this area, and others related to it, are likely to have a substantial effect on both the diffusion of 5G networks and the distribution of rewards across industry participants.

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- ¹ See, e.g., R. Bekkers, *Mobile Telecommunications Standards* (Boston and London: Artech House, 2001), pp. 234–241, 321–327.
- ² See, e.g., Order Granting in Part and Denying in Part Motion for Temporary Restraining Order, *Epic Games v. Apple Inc.*, No. 4:20-cv-05640-YGR (N.D. Cal. Aug. 24, 2020), <https://casetext.com/case/epic-games-v-apple-inc>.
- ³ The economic literature on system-type products is large. For a summary of the key issues, see H. Varian, “Competition and market power,” in: H. Varian, J. Farrell, and C. Shapiro, *The Economics of Information Technology* (Cambridge: Cambridge University Press, 2004), especially pp. 42–45. See also C. Shapiro and H. Varian, *Information Rules: A Strategic Guide to the Network Economy* (Cambridge: Harvard Business School Press, 1999).
- ⁴ See, e.g., G. Garrard, *Cellular Communications: Worldwide Market Development* (Boston and London: Artech House Publishers, 1998); H. Gruber, *The Economics of Mobile Telecommunications* (Cambridge: Cambridge University Press, 2005).
- ⁵ A. Cohen et al., “Protecting their intellectual assets: appropriability conditions and why U.S. manufacturing firms patent (or not),” NBER Working Paper No. 7552, February 2000.
- ⁶ Sometimes a distinction is made between “open in the process” and “open in the outcome.” A system is open in the process if the process of shaping the system is open to the participation of all interested stakeholders. A system is open in the outcome if its key specifications are available to everybody, and especially if the system is licensed to all interested parties at a reasonable rate. See J. West, “Seeking open infrastructure: contrasting open standards, open source, and open innovation,” *First Monday* 12:6 (June 2007); T. Simcoe, “Open standards and intellectual property rights,” in: H. Chesbrough et al., editors, *Open Innovation: Researching a New Paradigm* (Oxford: Oxford University Press, 2008).
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- ¹⁰ In the history of computers, this is precisely what happened to the UNIX operating system. See, among others, D. Garcia-Swartz and M. Campbell-Kelly, “Openness as a business strategy: Historical perspectives on openness in computers and mobile phones,” *Information Economics and Policy* 48 (September 2019), pp. 1–14.
- ¹¹ A. Mehrotra, *Cellular Radio: Analog and Digital Systems* (Boston: Artech House, 1994), pp. 146–150.
- ¹² J. Funk, *Global competition between and within standards: The case of cellular phones* (Houndmills and New York: Palgrave, 2002), pp. 43–45. To our knowledge, this book was the first to make the argument that open first-generation cellular standards led to faster cellular adoption than closed first-generation standards. The number of subscribers comes from the International Telecommunications Union (ITU) database.
- ¹³ Garrard, *Cellular Communications*, pp. 23–124.
- ¹⁴ On Japan, see U.S. International Trade Commission, *Global Competitiveness of U.S. Advanced-Technology Industries: Cellular Communications* (Washington DC: ITC, 1993), especially p. 4–4; Garrard, *Cellular Communications*, pp. 359–361; Gruber, *Economics of Mobile Telecommunications*, pp. 26–28, 135–139. On the United States, see Garrard, *Cellular Communications*, pp. 30–47; Gruber, *Economics of Mobile Telecommunications*, pp. 123–135. On the Scandinavian countries, see S. Hultén and B. Mölleryd, “Mobile Telecommunications in Sweden,” in: K. Schenk et al., editors, *Mobile Telecommunications: Emerging European Markets* (Boston: Artech House, 1995), pp. 1–28; J. Meurling and R. Jeans, *The Mobile Phone Book* (London: Ericsson Radio Systems AB, 1994), pp. 27–33; Garrard, *Cellular Communications*, pp. 48–61. The Scandinavian standard NMT generated academic interest because it was the first to allow roaming across countries. See T. Haug, “A commentary on standardization practices:

- lessons from the NMT and GSM mobile phone standard histories," *Telecommunications Policy* 26 (2002), pp. 101-107; J. Lehenkari and R. Miettinen, "Standardization in the construction of a large technological system—the case of the Nordic mobile telephone system," *Telecommunications Policy* 26 (2002), pp. 109-127.
- ¹⁵ On Germany, see M. Berlage and T. Schnöring, "The Introduction of Competition in German Mobile Communications Markets," in: K. Schenk et al., editors, *Mobile Telecommunications: Emergent European Markets*, pp. 29–49, Garrard, *Cellular Communications*, pp. 74–76, and Gruber, *Economics of Mobile Telecommunications*, pp. 105–108. On Italy, see Garrard, *Cellular Communications*, pp. 76–79, and Gruber, *Economics of Mobile Telecommunications*, pp. 108–112. On France, see Garrard, *Cellular Communications*, pp. 79–83, and Gruber, *Economics of Mobile Telecommunications*, pp. 112–115. On the UK, see especially T. Valletti and M. Cave, "Competition in UK mobile communications," *Telecommunications Policy* 22:2 (March 1998), pp. 109–131, and see also M. Armstrong, S. Cowan, and J. Vickers, *Regulatory Reform: Economic Analysis and British Experience* (Cambridge: The MIT Press, 1994), Garrard, *Cellular Communications*, pp. 95–124, and Gruber, *Economics of Mobile Telecommunications*, pp. 98–105.
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- ¹⁹ There were three types of cellular phones in the 1980s: car phones, transportable phones, and portable (handheld) phones. See U.S. International Trade Commission, *Global Competitiveness of U.S. Advanced Technology Industries: Cellular Communications*, pp. 1–3, 1–4.
- ²⁰ Smartphones have four types of semiconductor components: baseband chips, application processors, connectivity chips, and memory chips. See Nomura Equity Research, "U.S. Semiconductor Primer," December 11, 2013, <http://pdf.zacks.com/pdf/NO/H4560776.PDF>, last accessed on February 14, 2021.
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