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Coopetition, standardization and general purpose technologies: A framework and an application

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A R T I C L E I N F O

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A B S T R A C T

We argue that coopetition and standardization are important dimensions in the analysis of general-purpose technologies (GPT). We synthesize ideas from GPT, standardization, and coopetition literatures and introduce a framework for empirical analysis of GPTs that are enabled by standards development and related coopetition. We apply this framework and analyze the role of coopetition in standardization of wireless cellular technology, which has been recently discussed as a GPT. We document that coopetition and standardization have been associated with increasing improvement, innovation spawning, and pervasiveness—the characteristics of GPTs—in the context of wireless cellular technology. The perspective of standardization and coopetition could shed further light on the technological progress and evolution related to emerging GPT candidates, such as artificial intelligence and blockchain.

1. Introduction

General purpose technologies (GPTs), such as steam, electricity, and information and communication technologies (IT and ICT), have been important drivers of technological progress (Bresnahan & Trajtenberg, 1995; Lipsey et al., 2005; Bresnahan, 2010; Bekar et al., 2018, Heikkilä & Wikström, 2021). In prior literature, IT and ICT have been considered GPTs (Basu & Fernald, 2007; Jovanovic & Rousseau, 2005; Kim et al., 2021; Liao et al., 2016; Vu et al., 2020), and currently, during the 4th Industrial Revolution, artificial intelligence (AI) has been considered the next big GPT (Brynjolfsson et al., 2021; Trajtenberg 2018; Vannuccini & Prytkova 2021). GPTs enable various use-cases in various application sectors (Bresnahan & Trajtenberg, 1995; Jovanovic & Rousseau, 2005), but the diffusion of GPTs may take time—often decades (Baron & Schmidt, 2014; Bresnahan, 2010; Jovanovic & Rousseau, 2005)—and in practice, actual GPTs are only afterwards identified as such based on the established criteria for GPTs (see Section 3). In this article, we argue that coopetition and standardization are important dimensions in the analysis of GPTs. We proceed to analyze a specific GPT, namely wireless cellular telecommunications technologies (for brevity, "cellular technology" hereafter),[1] which belongs under the umbrella of ICT (Lindmark, 2005), and show how standardization and coopetition have been associated with the development of this

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[1] Cellular telecommunications technologies are the focus of the 3rd Generation Partnership Project (3GPP), https://www.3gpp.org/about-3gpp/.

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broadly standardized GPT.

While standards have played a major role in technological progress (Spencer & Temple, 2016; Yate s & Murphy, 2019) as well as in the development of markets, such as the European Single Market, the role of standards development has been a neglected topic in the context of economic growth theory until recently (Baron & Schmidt, 2014; Blind et al., 2022; Blind & Jungmittag, 2008; Heikkilä et al., 2021). Rosenberg and Steinmueller (1980) already noted the importance of standardization as a driver of economies of scale and noted that "*Standardization and connection standards may seem purely technical details to the casual observer, but in fact they reflect the importance of achieving economies of scale.*" Yet, the role of standards as a focal mechanism in technology diffusion and as an enabler of network effects and complementary innovations seems to need more attention.

Heikkilä and Wikström (2021) documented that the most common examples of GPTs (steam, railway, electricity, IT and ICT) have been subject to standardization efforts over time, suggesting that standards development has impacted the technological progress in these fields. Here, we focus on cellular technology, which is among the most important and widely used standardized global technologies: in 2022Q4, there are estimated to be more than 11 billion mobile cellular subscriptions.[2] In the current controversial and non-hierarchical classification of GPTs (Bekar et al., 2019), cellular communication belongs under the umbrella term ICT.

Standards play a particularly important role in the field of ICT (Blind & Gauch, 2008; Teubner et al., 2021), as the core function of ICT is to enable data, information, and idea flows over the interfaces ("communication") of global communication networks. For example, smartphone markets are enabled by global open standards, namely standards developed in the 3rd Generation Partnership Project (3GPP) and in the Internet Engineering Task Force (IETF), complemented by many other standards, for instance, for related radio technologies, applications, service provisioning, and testing. Lindmark (2005, p. 53) already noted that "*mobile data has the potential to become a general-purpose technology (GPT), since it is used in a wide range of applications, exhibits rapid and persistent performance improvements and strong innovational complementarities*." Now, almost twenty years later, we may revisit this analysis and ask whether cellular technology has become a GPT enabled by standards and coopetition.

This article contributes to the emerging literature connecting the analysis of GPTs and standards development (Baron & Schmidt, 2014; Heikkilä & Wikström, 2021; Lindmark, 2005; Martinelli et al., 2021; Parcu et al., 2022a; Simcoe, 2015; Teece, 2018; Thoma, 2008) by linking them to the burgeoning coopetition literature (e.g., Basole et al., 2015; Bengtsson & Kock, 2000; Devece et al., 2019; Gernsheimer et al., 2021). Standards development is a prime setting to analyze concurrent collaboration and competition (Leiponen, 2008; Oshri & Weeber, 2006)—that is, coopetition between companies. Dyadic links have already been made between these strands of research literature, but the aim here is to synthesize their intersection. Whereas the standardization perspective may add more structure and boundaries to the empirical analysis of GPTs and provide a more complete picture of the evolution of GPTs (Heikkilä & Wikström, 2021), a coopetition perspective makes visible the collaboration and competition between companies developing and implementing GPTs. Certain established "canonical" criteria, or necessary conditions, for GPTs exist (Bresnahan & Trajtenberg, 1995; Brynjolfsson et al., 2021; Goldfarb et al., 2023; Jovanovic & Rousseau, 2005), but there are no clear-cut thresholds—that is, explicit sufficient conditions when a potential GPT reaches the level of a "true" GPT.[3] Adding the coopetition perspective means that information on evolving collaborative and competition relationships may shed further light on the dynamic evolution of a GPT and related innovational complementarities. We demonstrate the usefulness of this analytical approach by applying it to cellular technology.

The paper is structured as follows. Section 2 introduces the conceptual background. Section 3 addresses the identified research gap in the intersection of GPT, standardization, and coopetition literatures and presents a framework to empirically analyze coopetition and standardization in the context of GPTs. In Section 4, we apply this framework to the case of cellular technology. Section 5 concludes.

2. Conceptual background

Standardization, GPT, and coopetition are concepts that are understood differently in different contexts.[4] Thus, we begin by explicitly defining what we mean by them here. A standard is by definition a document *"established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context,"* and "standardization" is the activity of establishing standards.[5] Standardization, in this context, refers generally to standards development in standards development organizations (SDOs) and more specifically to open, voluntary, and consensus-based standardization (Yates and Murphy, 2018). The impacts of standards can be manifold and are context-specific (Swann, 2010). Also, motives to participate in standardization can be manifold and may include, among others, designing industry-friendly regulations, enforcing company-specific content in standards, preventing formal standards that conflict with one's own interests, solving industry-specific technical problems, acquiring knowledge in committee discussions, and keeping track of other companies' technical knowledge (Blind & Mangelsdorf, 2016).

GPTs are specific types of technologies that fulfil certain criteria: They are pervasive, improve continuously, and spawn innovation (Bresnahan, 2010; Bresnahan & Trajtenberg, 1995; Heikkilä & Wikström, 2021; Jovanovic & Rousseau, 2005). Here we focus particularly on identification of GPTs based on these criteria (see Section 3). According to Jovanovic and Rousseau (2005), GPTs

[2] GSMA statistics https://www.gsma.com/Accessed 17 Apr 2022.

[3] For instance, Teece (2018), Martinelli et al. (2021), and Parcu et al. (2022b) make distinctions between GPTs and enabling technologies.

[4] For an overview of different perspectives, see, e.g., Grillo et al. (2021) and Heikkilä et al. (2021)for standardization, Bekar et al. (2018) for GPTs, and Bouncken et al. (2015)for coopetition.

[5] ISO/IEC GUIDE 2:2004 "Standardization and related activities—General vocabulary."

describe a new method of producing and inventing that is important enough to have a protracted aggregate impact. The concept has been criticized for its controversies but is still considered useful for economic theory (Bekar et al., 2018).

The concept of coopetition was coined by Brandenburger and Nalebuff (1996). It refers to the simultaneous cooperation and competition between rival firms to create value (Gernsheimer et al., 2021). According to Bouncken (2015, p.591): "*Coopetition is a strategic and dynamic process in which economic actors jointly create value through cooperative interaction, while they simultaneously compete to capture part of that value.*" It is important to note that several studies analyze simultaneous collaboration and competition (e.g., Leiponen, 2008) without explicitly referring to the phenomenon as "coopetition." In the context of standardization, Riillo et al. (2022, p. 1) defined that coopetition *"refers to competitors cooperating in setting a standard."*

Fig. 1 illustrates the strands of literature that we aim to combine, and we focus on the intersection of all three. The literature review is divided into three sections. First, we review the literature that discusses the role of standardization in the context of GPTs. Second, we discuss the literature linking coopetition and standardization. Third, we review the literature that links coopetition to the development of GPTs. In the succeeding Section 3, we make our contribution to the literature and shed light on the research gap at the intersection of the analyzed strands of literature by synthesizing how the lens of coopetition may improve our understanding of its role in the development of standardized GPTs (area 4 in Fig. 1).

2.1. *Standardization–GPT link*

Institutions matter for economic growth (Acemoglu et al., 2005; North, 1991). It has been noted that SDOs can be interpreted as institutions or "rules of the game" (Blind & Jungmittag, 2008; Heikkilä et al., 2021). According to North (1991, p. 97), "*Throughout history, institutions have been devised by human beings to create order and reduce uncertainty in exchange,*" and he also notes that "*Effective institutions raise the benefits of cooperative solutions or the costs of defection*" (p.98). Standardization may reduce uncertainty in the adoption and diffusion of technologies (Swann 2010) including GPTs. Bresnahan and Trajtenberg (1995, p. 96), who coined the term GPT, referred themselves to formal standards-setting processes, among others, as mechanisms that have emerged for coordinating and directing technical progress. They also noted that such mechanisms may permit revelation of the likely direction of technical advance within particular technologies and the encouragement of complementary innovations.

Thus far, some studies have linked standardization and GPTs (e.g., Baron & Schmidt, 2014; Heikkilä & Wikström, 2021; Martinelli et al., 2021; Simcoe, 2015; Teece, 2018; Thoma, 2008). However, there is still relatively little understanding of how standardization may foster the emergence and diffusion of GPTs. According to economic growth theories, technological progress relies on the accumulation of technological knowledge, but they typically abstract away the distinction between tacit and codified knowledge (Cowan et al., 2000). Standardization as codification of technical knowledge into technical specifications presumably plays an important role in the accumulation of technological knowledge and in determining technological trajectories (Kim et al., 2017; Swann 2010). For instance, Spencer and Temple (2016) analyzed standardization through the British Standards Institution (BSI) over the period 1931–2009 and found that the strong growth of the standards made available via the BSI catalogue has been associated with a large proportion of measured technological change and labor productivity growth. Several studies have also emphasized that significant knowledge spillovers can be related to standardization processes (Blind & Mangelsdorf, 2016; Leiponen, 2008).

Furthermore, standardization drives compatibility, which enables interoperability, and therefore standardization is a major driver for network effects (Gandal, 2002). Network effects, on the other hand, strengthen the position of ecosystems utilizing the standardized compatibility, which in case of GPTs makes the position of such technology candidates much stronger. Additionally, standardized interfaces allow complementary products and applications to be provided on the top of the GPT (Swann, 2010). The other main purposes of standardization, such as verifiable quality and reduction of variations, may drive the role of the focal GPT even further. In addition, governments are often very keen to drive regulative requirements through their annual work programs for formal SDOs.[6]

Heikkilä and Wikström (2021) explored the links between standards and GPTs and documented that all the most common examples of GPTs (steam, railway, electricity, IT and ICT) have been subject to standardization efforts over time. They concluded that "*Generally, viewing the evolution of GPTs via the lens of standards development may help future GPT research in providing structure and hierarchies, thus making the empirical analysis of GPTs more systematic.*"

Although the GPT literature discusses ICT as one unit, there is naturally no single "ICT" but a set of technologies that belong under the umbrella of ICT. However, technologies under the ICT umbrella are quite strongly connected to each other—as technologies but also via companies (Basole et al., 2015) and as standards utilized in ICT products (Ali-Vehmas, 2016). Particularly in the ICT sector, standardization enables interoperability and creation of network effects, and as a consequence, all current platform businesses are built upon standardized ICTs (incl. internet).[7] According to Baron and Spulber (2018, p. 487 Table.1), the most salient trend in the number of standards issued is the increasing importance of telecommunications and IT over time.

2.2. *Standardization–coopetition link*

The notion of concurrent collaboration and competition in the context of standards development is not a novel idea. Even Brandenburger and Nalebuff (1996, pp. 37–38) themselves noted in their seminal book "Co-opetition" that "*Today competing hi-tech companies are regularly joining forces to build infrastructure and standards for the information economy*." Since then, for instance, Oshri

[6] https://ec.europa.eu/growth/single-market/european-standards/notification-system_en#annual Accessed 3 Feb 2022.

[7] https://ec.europa.eu/growth/single-market/european-standards/ict-standardisation_en Accessed 3 Feb 2022.

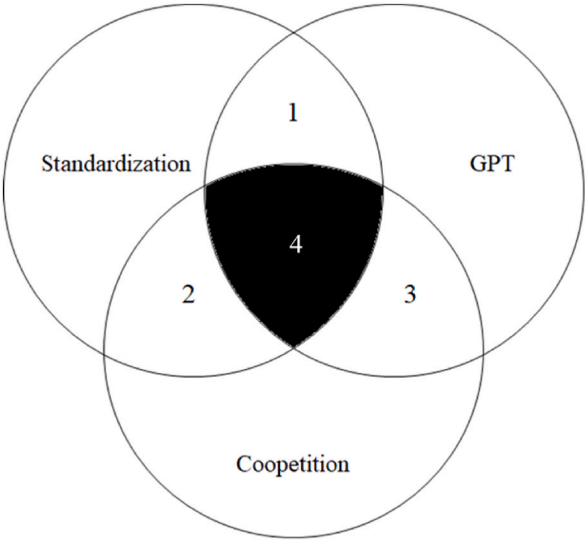

Fig. 1. Intersections between streams of literature.

and Weeber (2006, p. 280) suggested the 'coopetition' concept as a useful lens to assess competitive and cooperative activities that members of a network undertake to coordinate standards-setting activities as a cooperative unit. Leiponen (2008) analyzed collaborative standards development in the context of wireless telecommunication and related competition between firms. Blind and Mangelsdorf (2016, p. 21) noted, "*joining standardization means entering into a specific type of coopetition. Involvement in standardization is typically a long-term commitment indicative of a strong interest to cooperate,* e.g.*, companies cooperating in standardization try to open up new markets by defining common standards, which either reduce barriers to trade or achieve compatibility with complementary products or systems*." Also, Mione (2009) made the explicit link between coopetition and standards development when analyzing entrepreneurs' decisions in the emerging geosynthetics market. She concludes that coopetition to establish standards appears to be a required phase of entrepreneurship strategy. Ali-Vehmas (2016) examined in detail the levels of coopetition in five different ICT SDOs based on the co-authoring in standardization contributions. In all forums, coopetition is an important element, while the variations depend on a number of factors, including the boundary conditions of the related value systems. Mione, 2018 suggested that "*standardization constitutes an ideal locus to explore coopetition from a strategic and managerial perspective.*"

Despite the burgeoning coopetition literature (Gernsheimer et al., 2021), the link between coopetition and standardization still seems weak. Five recent literature reviews of coopetition (Bengtsson & Raza-Ullah, 2016; Bouncken et al., 2015; Devece et al., 2019; Dorn et al., 2016; Gernsheimer et al., 2021) pay only limited attention to standardization. As an exception, Dorn et al. (2016, p. 489) noted that "*coopetition is also likely to occur in an early market lifecycle stage; for example, if there is a need for rapid standard-setting (Gnyawali & Park, 2011; Oshri & Weeber, 2006).*"

2.3. Coopetition–GPT link

Coopetition analysis has been applied to various industries, contexts, and levels of analysis (Gernsheimer et al., 2021). However, there seems to be no explicit link made between coopetition and the development of GPTs. In the Web of Science and Scopus databases, a simple keyword search query for "coopetition" AND "general purpose technology" in either article title or abstract retrieved no results in November 2022. Also, none of the five recent literature reviews of coopetition research (Bengtsson & Raza-Ullah, 2016; Bouncken et al., 2015; Devece et al., 2019; Dorn et al., 2016; Gernsheimer et al., 2021) mentions GPTs.

On the one hand, ICT has been viewed as a GPT in various studies (e.g., Heikkilä & Wikström, 2021; Jovanovic & Rousseau, 2005; Kim et al., 2021), and its impact on economic growth has been analyzed extensively (see, e.g., Vu et al., 2020 for a recent overview). On the other hand, coopetition has been linked to ICT standardization (Section 2.2 above). Recently, for instance, Basole et al. (2015) quantified and visualized coopetition in the ICT ecosystem, noting increasing coopetition yet at a decreasing rate. Thus, the ICT sector provides probably the most fruitful context in which to analyze the link between coopetition and GPTs.

3. Framework: Standardization and coopetition enabling GPTs

The simple framework presented here builds on the intersection between standardization, coopetition, and GPT literatures and aims to elaborate the empirical analysis of GPTs. The key proposition is that integrating coopetition and standardization perspectives in the analysis of GPTs would increase our understanding of how GPTs are developed in practice. Jovanovic and Rousseau (2005) provided a blueprint for the holistic measurement of GPTs, but they did not consider the role of standardization and coopetition in promoting the key GPT characteristics. Empirical studies of GPTs can be roughly divided into two categories: those focusing more on identifying GPTs by measuring their characteristics and those focusing more on analyzing or measuring the economic impacts of GPTs. Here, the focus is on the former. The key characteristics of a GPT boil down to the following three (Bresnahan, 2010; Bresnahan & Trajtenberg, 1995; Goldfarb et al., 2023; Heikkilä & Wikström, 2021; Jovanovic & Rousseau, 2005; Vu et al., 2020; Youtie et al., 2008).

1) **Pervasiveness**—A GPT should spread to most sectors.
2) **Improvement**—A GPT should become better over time and thus, keep lowering the costs of its users.
3) **Innovation spawning**—A GPT should make it easier to invent and produce new products or processes.

It should be noted that fulfilling these necessary conditions of a GPT says little about the sufficient conditions that need to be fulfilled before a technology can be classified as a GPT. There are no objective, clearly defined thresholds for these sufficient conditions. At the extreme, full pervasiveness could be said to be achieved only when all (existing) sectors and/or all users are implementing the GPT. In the case of improvement and innovation spawning, there are no similar clear maxima, as the limits increase over time and are inherently uncertain by nature when new innovations and application sectors are developed. In other words, dynamic radical uncertainty (or Knightian uncertainty, Knight, 1921) related to technological progress makes it impossible to define explicit and absolute sufficient conditions for GPTs.

A key element of GPTs is the positive feedback loop in innovation activity, or innovational complementarities, within and between (i.e., horizontal and vertical spillovers) the GPT developing ("upstream") sector and the application sectors (AS, "downstream") that implement the GPT (Bresnahan, 2010; Bresnahan & Trajtenberg, 1995). According to Bresnahan and Trajtenberg (1995, p. 84), "innovational complementarities" means that "*the productivity of R&D in a downstream sector increases as a consequence of innovation in the GPT technology. These complementarities magnify the effects of innovation in the GPT, and help propagate them throughout the economy.*" According to Bresnahan (2010, p. 764), "innovational complementarities" comprises combination of characteristics 2 and 3 above—that is, the GPT is both capable of ongoing technical improvement and enabling innovation in application sectors (AS)—or more precisely, innovations in the GPT "*raise the return to innovations in each AS and vice versa.*"

When analyzing any GPT, it is important to understand the industry structure and institutional setting. What factors impact the incentives of the companies in the GPT developing sector and application sectors? Which institutions, regulations, and SDOs define the "rules of the game"? We presume that it is possible to shed light on the industry dynamics and spillovers within and between GPT developing and application sectors by analyzing the behaviors of companies that participate in standards development and submit technical documents (cf. Ali-Vehmas, 2016; Johansson et al., 2019; Leiponen, 2008).

The strand of literature that empirically analyzes GPTs uses different non-standardized units of analysis and empirical observations when identifying GPTs because the described GPT criteria are ambiguous. Connecting GPTs to relevant SDOs and standardization events may help researchers to focus on specific units of analyses and observations (Heikkilä & Wikström, 2021). The International Classification for Standards may offer guidance here and direct focus on relevant standards classes (cf. Baron & Schmidt, 2014; Blind & Gauch, 2008). Researchers can potentially get additional insight to the GPT criteria and relevant units of analysis from the materials of the relevant SDOs (incl. their mission, performance criteria, datasets, etc.). For instance, Teubner et al. (2021) illustrate the large number of SDOs and related organizations around ICT that may serve as important information sources when analyzing ICT as a GPT.

The fourth dimension that we would add to the empirical analysis of GPTs is standardization, as suggested by Heikkilä and Wikström (2021), and related coopetition. Presumably, standards development and coopetition may impact all dimensions of a GPT: pervasiveness, improvement, and innovation spawning. In the context of standards development, technology improvements typically take place first, innovation spawning follows, and finally pervasiveness is the measure of how complete the process is. Fig. 2 illustrates the conceptual model. Since the relationships are intertwined and endogenous, and the identification of causal effects is confounded by feedback loops, we illustrate the associations with arrows going in both directions. Moreover, while not explicitly illustrated in Fig. 2, there are naturally other confounding factors that impact the evolution of GPT characteristics. We make the following propositions.

Proposition 1. *Standardization and coopetition are positively associated with improvements related to the GPT.*

Proposition 2. *Standardization and coopetition are positively associated with innovation spawning related to the GPT.*

Proposition 3. *Standardization and coopetition are positively associated with pervasiveness of the GPT.*

While a large proportion of previous empirical GPT studies has focused on analyzing specific characteristics of GPTs or applied specific methods (e.g., patents statistics: Moser & Nicholas, 2004; Feldman & Yoon, 2012; Petralia, 2020), a mixed methods approach combining both quantitative and qualitative analyses of multidimensional GPT characteristics (improvement, innovation spawning, and pervasiveness) presumably provides a more holistic and rigorous analysis (cf. Jovanovic & Rousseau, 2005). Fig. 2 provides a few examples on operationalization of the measurement of GPT criteria (not to be considered as an exhaustive list). Next, we apply this framework to cellular technology.

4. Application: the case of cellular technology

While ICT is a common example of a GPT (Basu & Fernald, 2007; Liao et al., 2016; Vu et al., 2020), there are many ICT standards and SDOs (Baron & Spulber, 2018; Teubner et al., 2021). We focus on one of the most pervasive ICTs, cellular technology, in order to be able to limit our attention to standardization and coopetition within a specific SDO, 3GPP. As a truly global standardized technology, cellular technology is an exemplar case that may inform future studies analyzing the role of standardization and coopetition underlying the evolution of GPTs.

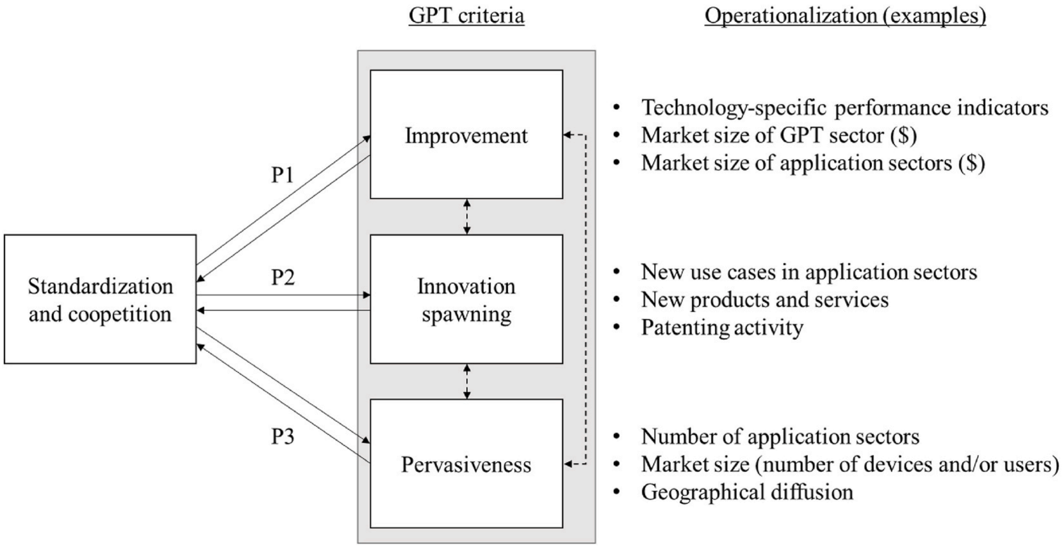

Fig. 2. Conceptual model.

We provide a descriptive analysis on the extent to which cellular technology satisfies the GPT criteria and how standardization and coopetition are related to the evolution of cellular technology. As suggested by Heikkilä and Wikström (2021), viewing the development from a standardization perspective may promote the systematic analysis of GPT evolution, but it should be kept in mind that the SDOs are necessarily GPT-specific. This context-specificity calls for GPT-specific case studies (cf. Simcoe, 2015; Thoma, 2008). In this study, we focus on the GPT criteria (Fig. 2) and utilize information from various sources, complementing market data with information from standards organizations relevant to cellular technology development (incl. 3GPP, the European Telecommunications Standards Institute (ETSI), the International Telecommunication Union (ITU)) up to the current mainstream generation, 5G.

Recently, the concept "GPT" has been related to 5G (Knieps & Bauer, 2022; Parcu et al., 2022a, 2022b; Teece, 2018)—the latest cellular technology standard generation. The online appendix provides selected examples of articles suggesting that cellular technology is a GPT. For instance, Parcu et al. (2022b, p. 3) state that "*5G is the first mobile generation that could possibly emerge as a General-Purpose-Technology (GPT), one that could acquire a standing almost comparable to electricity or the Internet.*" Previously, Lindmark (2005) analyzed "mobile data communication" as a GPT and concluded that it exhibits characteristics typical for GPTs, though not all—since usage levels were relatively low in early 2000s. Now, more than 15 years later, it is clear that service quality has increased (improvement), there are increasingly use cases and applications enabled by mobile data communication (innovation spawning), and the volume and number of mobile data communication users have increased (pervasiveness).

4.1. Standardization and coopetition facilitating evolution of cellular technology

Over the last four decades, multiple cellular technologies have converged to one mainstream system based on the specifications developed in the 3GPP (Baron & Gupta, 2018). The 3GPP was set up in 1998 to drive the evolution of 3G based on the Global System for Mobile Communications (GSM, originally *Groupe Spécial Mobile*) technology and standardization carried out in the ETSI. In Europe, the consolidation from several different incompatible 1G systems toward one pan-European 2G system—that is, the GSM system—started as early as 1982 based on the decisions by the national governments in the context of the European Conference of Postal and Telecommunications Administrations (CEPT) (see Dunnewijk & Hultén, 2007). Hawkins (2017, p. 71) noted that GSM as *"the first digital wireless standard, set up the pathway towards today's smartphones and the explosion in apps, which themselves are dependent on common interface and programming standards.*[8]".

This development gained global momentum in the 3GPP, which responded to the global spectrum policies defined in the ITU (Clark & Claffy, 2015; Tadayoni et al., 2018). During the 3G era, global consolidation was not complete, but during the evolution through 3.5G, 4G, and finally to 5G, all countries have acknowledged the central role of the 3GPP in creating the specifications for cellular telecommunications technologies. Today, the national and regional formal SDOs adopt the 3GPP specifications as the formal cellular technology standards. This common, standardized technology platform carries the heritage not only in the name but also in the architecture, governance, and process that were initially developed for international pan-European coopetition.

[8] See http://www.3gpp.org/about-3gpp/about-3gpp, Accessed 3 Feb 2022. Among others, Lyytinen and Fomin (2002), Manninen (2002), and Lehenkari and Miettinen (2002) describe the history preceding the 3GPP, while Ahava (2015) and Ali-Vehmas (2019) provide descriptions of the 3GPP's history. The functioning of the 3GPP has been described and analyzed in an increasing number of studies (Ali-Vehmas, 2016; Baron & Gupta, 2018; Johansson et al., 2019; Jones et al., 2021; Leiponen, 2008; Teubner et al., 2021).

The objectives of the 3GPP have evolved based on market needs and technology capabilities, but there are some uncompromised principles worth noting related to system boundaries and technology architecture, as well as to the balance between competition and collaboration. The main elements include globally agreed spectrum bands, the central role of licensed mobile operators, a regulation driven system architecture with a number of uncompromised open standardized interfaces, and finally, the strong role of consumers to choose the service and products they like. Now, as the 3GPP-developed technology evolves toward 6G, the scope has widened to also include ecosystems where more diverse competition models will be available, including private networks, government services, and unlicensed spectrum bands (Yrjölä et al., 2022; Ziegler & Yrjölä, 2021). With these expansions, 3GPP cellular technology is becoming pervasive in a significantly broader sense than ever before.

Coopetition in standardization of cellular technology has some specific characteristics due to the governance rules of the related value system, i.e., the licensed mobile operators, including their suppliers and customers. Cooperation in 1G was limited as national monopoly telecom operators strongly controlled the process, standards, and business. In Nordic countries, however, a slightly different approach was chosen. During the years 1969–1982, The Nordic mobile telephone system (NMT) was collaboratively developed by the national authorities of Finland, Sweden, Norway, and Denmark. This multinational collaboration influenced the way the 2G technology was developed in the CEPT context and later in ETSI, where competition also became important (Lehenkari & Miettinen, 2002; Manninen, 2002). The coopetition in 5G standardization in the 3GPP inherited the process principles from 2G (GSM) even as the coopetition extended to include the preferences of actors worldwide.

In the 3GPP, the relatively low number of licensed mobile operators drives local oligopolistic markets at the national level, limiting competition, while the mandated interoperability requirements facilitate collaboration at the global level. In contrast, Over the Top (OTT) service capabilities are not standardized in the 3GPP but rather through internet-driven communities, such as the Internet Engineering Task Force (IETF), the World Wide Web Consortium (W3C), and numerous other voluntary organizations. Furthermore, most of the actual OTT services are driven by competing companies and applications, without standardization but rather with the aim of establishing a position as a dominant design. Here, we focus on coopetition related to the technologies and standards of the network layer, i.e., the 3GPP-specified functionalities. The specific models of collaboration and competition are distinctively different in the mobile operator-controlled network layer compared to the other layers (cf. Ali-Vehmas, 2016; Fransman, 2002).

Technical solutions compete first in the standards development phase and then in the market, where products implementing the technical solutions compete (Blind & Mangelsdorf, 2016). Leiponen (2008), Delcamp and Leiponen (2014), and Baron and Gupta (2018) reported that hundreds of firms have participated in the development of cellular technology standards. For instance, Baron and Gupta (2018) identified 489 distinct members (parent entities) in the 3GPP between 2000 and 2014. However, the number of active contributing companies is smaller, as some dozens of companies have produced the majority of the contributions (Baron & Gupta, 2018, esp. Fig. 6 and Table 1 p. 447). Johansson et al. (2019) examined the interdependence between research and development resources, coopetitive performance, and extent of cooperation in development-related standardization settings that involve network effects. They analyzed the 3GPP change request database and found support for the hypothesis that R&D resources are associated with coopetitive performance in innovation-related coopetitive settings with network effects. Fig. 3 illustrates the increasing number of new memberships over time as reported by 3GPP. Higher numbers of members imply more potential coopetition relations.

Elected chairs and vice chairs of the technical specification groups (TSGs) and working groups (WGs) of the 3GPP (see Fig. A.1 in the Appendix for the organizational structure of the 3GPP) are responsible for the overall management of the technical work within the TSGs and WGs and their sub-groups, according to the 3GPP Working Procedures. In performing their leadership role and conducting the meetings, "*the chairs and vice chairs shall maintain impartiality and act in the interests of 3GPP.*"[9] Importantly, to ensure the international distribution of positions of trust, the chairs and vice chairs should not be from the same region. Fig. A.2 in the Appendix shows the organizations of alternating elected chairs and vice chairs in plenaries of the three TSGs over time, further demonstrating how companies collaborate in developing the technical specifications and act in turn in important positions of trust. To summarize, 3GPP is a major standards development forum where collaboration, competition, and coopetition occur and whose aim and mission is, in essence, to promote improvement, innovation spawning (innovational complementarities), and pervasiveness of standardized cellular technology.

4.2. Characteristics of standardized cellular technology

Originally in 1G, mobile cellular technology was developed for a very focused service: voice communication specifically for each national market. Each generation has brought more and more features and functionalities (improvements) that support a wider and wider set of applications (innovation spawning) in larger and larger geographical contexts serving more and more application sectors and people (pervasiveness). Next, each of the three established GPT criteria related to cellular technology are discussed in both qualitative and quantitative dimensions.

4.2.1. Improvement

Mobile cellular communication has shown remarkable evolution over the last 40 years. The technologies, products, and services have evolved from the basic cellular radio system of 1G through digitalization, signal processing enhancements, and network protocol renewals to the current 5G. Those improvements have enabled new capabilities, such as multiple audio and video coding capabilities,

[9] https://www.3gpp.org/ftp/Information/Working_Procedures/3GPP_WP.htm#Article_23 Accessed 21 Jun 2022.

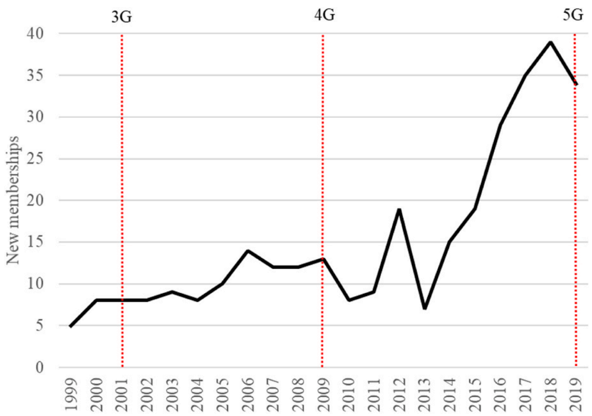

Fig. 3. New 3GPP memberships. The source is the 3GPP, https://www.3gpp.org/news-events/3gpp-wiki/9-news-events/3gpp-news/2124-members700 Accessed Apr 8, 2022.

utilization of a large range of different radio spectrum allocations, using broad sets of access (Frequency Division Multiple Access FDMA, Time Dimension Multiple Access TDMA, Code Division Multiple Access CDMA, Orthogonal frequency-division multiple access OFDMA) and duplexing (Frequency-Division Duplex FDD, Time-Division Duplex TDD) techniques, and remarkable network level capabilities like massive MIMO; these are all supported by AI mechanisms that are all incorporated into the very same backward-compatible system. Tadayoni et al. (2018) provided a more detailed overview of improvements by cellular technology generations and 3GPP releases. As a qualitative summary, Table 1 in Section 4.3 below shows some selected milestone improvements.

Quantitatively, the most visible evidence of the continuous improvement process is the evolution of the available data rates in the mobile cellular communication. Peak data download rate is one important measure of performance of mobile data services. Fig. 4 shows the exponential development (nb. the logarithmic scale, cf. Moore's law) over time and corroborates the observations of Lindmark (2005, Fig. 1, p.46) by showing that the improvement has continued over time. However, it should be noted that data rate is only one dimension that has improved concurrently with continuous standards development. Other simultaneous multi-dimensional improvements include energy efficiency (extended battery life), lower latency, increased reliability, extended coverage, and spectral efficiency (Tadayoni et al., 2018). Moreover, Fig. 5 illustrates (in the case of Finland) how voice calls used to be the most important consumer "app" in cellular networks, where the usage (minutes per capita) has been relatively stable over time (nb. uptick during COVID-19). Since the beginning of the smartphone and 4G era, data traffic per capita has increased significantly. It is worth mentioning that all these improvements have been developed in parallel when the quality-adjusted prices of the corresponding products and tariffs of the services have reduced.

The development of cellular standards is a complex and dynamic process where contributors simultaneously improve various dimensions. Baron and Gupta (2018, p. 440) describe the development of 3G and 4G standards by noting that: "*These evolutionary steps in the technology come from the combination of research and development efforts from hundreds of firms investing billions of dollars in R&D (Gupta, 2013). The development of these standards is broken up into various releases. Each release is made up of hundreds of TSs [technical specifications] that have been built by thousands of contributions made by hundreds of firms.*" One can get an understanding of the multidimensional 3GPP standards development work by viewing the priorities of different technical specification groups for subsequent "releases." According to 3GPP, "*3GPP uses a system of parallel 'Releases' which provide developers with a stable platform for the implementation of features at a given point and then allow for the addition of new functionality in subsequent Releases.*"[10] The latest release is Release 18, for which the timeline, plans, and contents can be viewed online.[11]

Research on standardization and coopetition emphasizes how both may enable value creation. The changing market size of application sectors measured in monetary terms provides a rough proxy for improvement in the context of a network good, such as mobile communication. According to St. Louis Fed, the total revenue for wireless telecommunications carriers[12] in the US increased from $126 B in 2004 to over $300 B in 2021, and since the 4G era enabled smartphone markets, global mobile phone sales revenue exceeded $400 B in 2016 (Galetovic et al., 2018) and total app revenues exceeded $100 B in 2018 (Gokgoz et al., 2021).[13] Moreover, it should be noted that the growth in related markets, such as mobile social media and mobile advertising, has also been very strong. The mobile advertising market has grown from virtually zero to tens of billions of USD during the 2000s (Campbell-Kelly et al., 2015) and

[10] https://www.3gpp.org/specifications/67-releases See also Tadayoni et al. (2018).

[11] https://www.3gpp.org/release18.

[12] Total Revenue for Wireless Telecommunications Carriers (Except Satellite), Establishments Subject to Federal Income Tax, https://fred.stlouisfed.org/series/REV5172TAXABL144QNSA#0 Accessed 3 Feb 2022.

[13] Aizcorbe et al. (2019) demonstrates that quality improvements in devices and services in the mobile phone markets are challenging to disentangle and price data does not always reflect the quality improvements.

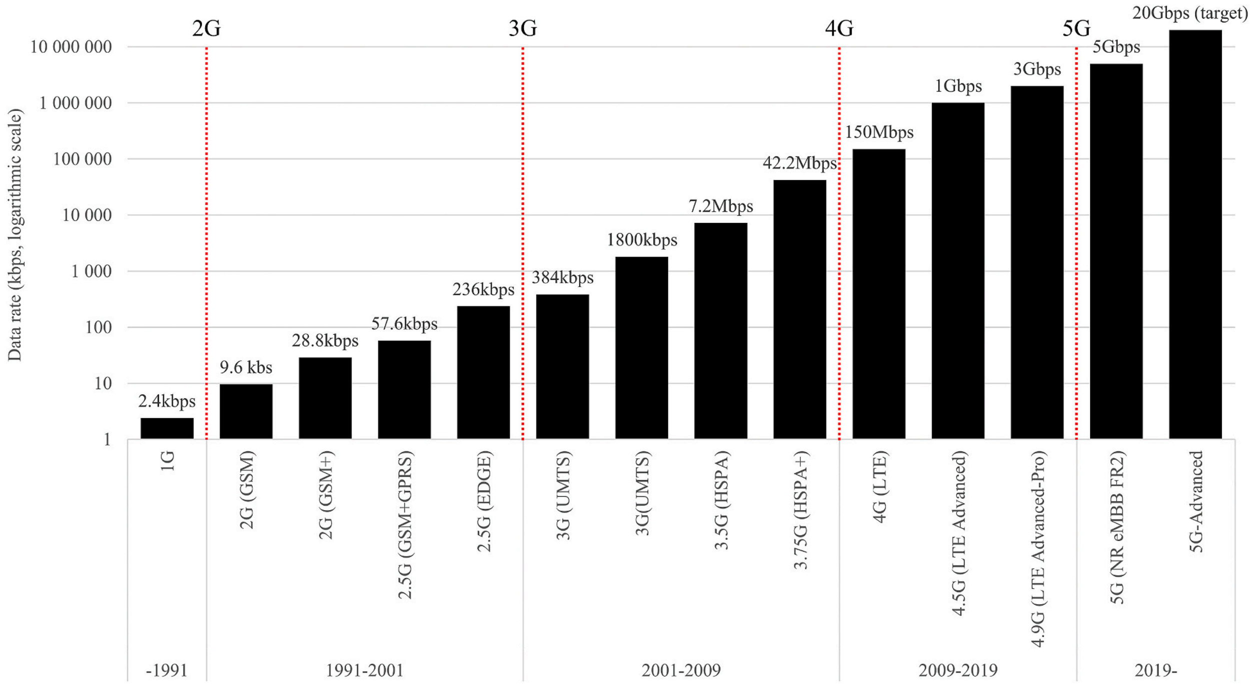

Fig. 4. Peak data rate. Peak data rate information is compiled from various sources.

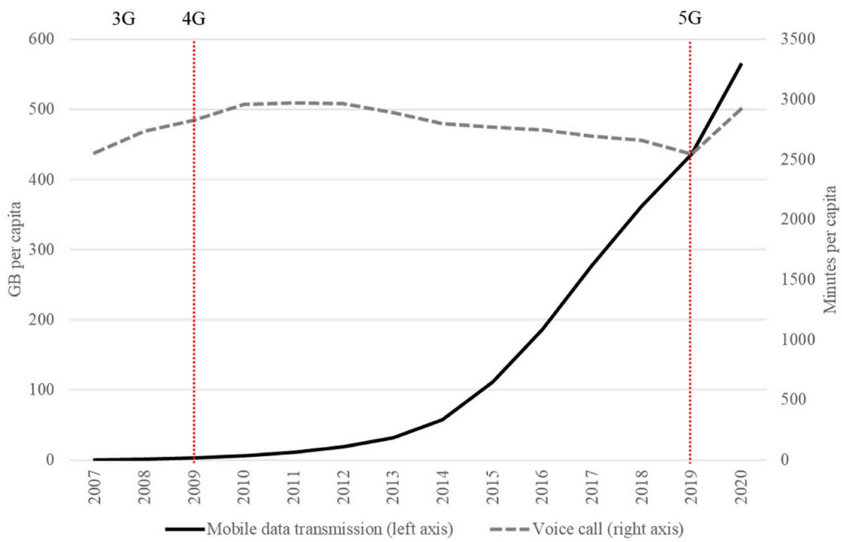

Fig. 5. Mobile data and voice traffic trends, Finland. The source of Finnish mobile data and voice traffic data information is Traficom, https://www.traficom.fi/en/statistics/volume-data-transferred-mobile-network-0 Accessed Feb 3, 2022.

recently exceeded $100 B.[14] We may conclude that continuous standardization and coopetition have been associated with multidimensional improvement of cellular technology, lending support to Proposition 1.

4.2.2. Innovation spawning

Innovation spawning in cellular technology was initially internally focused. The mobile operators enjoyed very strong monopoly positions in 1G, and due to the lack of open interfaces, any innovation was integrated into the system itself. Manninen (2002, p. 99)

[14] https://www.statista.com/outlook/dmo/digital-advertising/social-media-advertising/worldwide Accessed 9 Nov 2022.

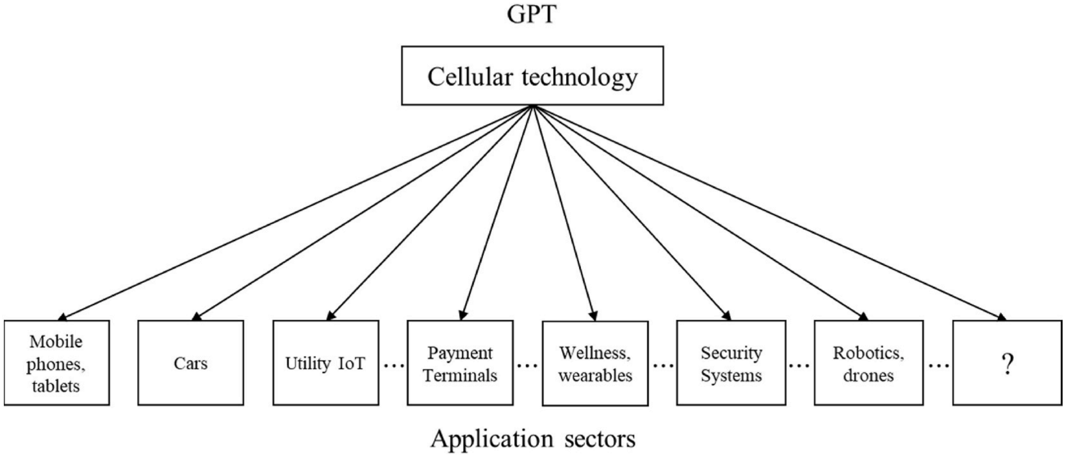

Fig. 6. Selected application sectors of cellular technology. Authors' illustration following the framework by Bresnahan and Trajtenberg (1995, p. 87 Fig. 1). The selected application sectors are illustrative and do not provide an exhaustive list.

notes that *"According to the Finnish ironic interpretation, everything not specifically allowed was forbidden."* This behavior continued in early 2G, when text messaging and later other supplementary services were gradually introduced (Vesa, 2006). However, some experimental OTT services were already being used in 1G and 2G, such as fax and email using audio modems and data channels, respectively. In addition, the general packet radio service (GPRS) enabled cost effective mobile-specific browsing (wireless application protocol, WAP) and other similar narrow-band vertically integrated services.

The 3G standard introduced relatively high-rate data services for end users, which enabled early internet-type applications to emerge, including browsing (standardized in the W3C) and mobile banking. This raised the question of whether the 3GPP was the optimal forum to drive standards for those clearly non-telecom services that were not defined in the telecom regulations. Concurrently, the wired internet was evolving fast, which was considered primarily a competitor to the mobile-specific internet. Therefore, a set of collaborative arrangements between the 3GPP and some new and existing SDOs were set up, namely with the Open Mobile Alliance (OMA) and with IETF, W3C, and also IEEE 802.11 for WiFi capabilities. These decisions enabled the possibility of very fast innovation spawning. The value chain thinking evolved toward value networks (Peppard & Rylander, 2006), which took place in close connection to related standardization groups, like the OMA, and in a rather loose mode with all the forums and organizations that were developing standards for the internet (Ali-Vehmas, 2016). As described above, the 3GPP focused on system improvements and a set of open interfaces, which facilitated innovation spawning on the top of the network layer. Many of the emerging OTT services and applications also required significant improvements in the 3GPP standards. This created a very powerful improvement and innovation spawning cycle—that is, innovational complementarities, as illustrated in Table 1 below. Fully international adoption of the new services was hampered by the lack of affordable data roaming, which was introduced for Europe as late as 2012 (Spruytte et al., 2017).

Today, the 3GPP system technologies and standards support a variety of use cases, including several smartphone and data platform ecosystems, and use cases with specific enhancements, such as embedded SIM for more and more integrated mobile device designs and DASH for video sharing over cellular.[15] Parallel to this, the 3GPP system enables innovations in many other sectors of business and life, ranging from automobile and railroad systems through satellite systems to several mission critical services that enable high performance industrial and governmental services to be built on top of the 5G platform. Internet of things (IoT) applications are multiplying the number of subscriptions far beyond the number of people on the planet (Edquist et al., 2021). According to Kim et al. (2017), 3GPP standards assume a crucial role in setting the boundary conditions of the M2M/IoT technological systems. It should be emphasized that innovation spawning requires continuous collaboration not only within each standardization organization separately but also between the SDOs (Clark & Claffy, 2015; Teubner et al., 2021).

As a growing number of sectors have adopted cellular technology and are intensifying its use in the era of IoT, there is an increasing potential for innovational complementarities within and between these application sectors and GPT-developing companies. As we are considering global telecommunication standards, in principle, the innovational complementarities are not limited to national settings by geographical borders. Knowledge spillovers in the standardization process characterized by coopetition are virtually inevitable (Blind & Mangelsdorf, 2016; Leiponen, 2008; Swann, 2010), and there can be appropriability challenges (Teece, 2018; Yang et al., 2022). Patent systems are institutions that aim to incentivize innovation activity by enabling appropriability of returns from R&D investments. While there are significant caveats to the use of patents as a proxy for innovations (Nagaoka et al., 2010), patent statistics are still one of the best available means to visualize trends in innovation activity and innovation-based competition (cf. Aghion et al., 2016).

Bekkers et al., (2020, p.25, Fig. 8) analyzed the patent landscape related to cellular standards and reported statistics on the number

[15] The 73rd Tech Emmy® was awarded to 3GPP. https://www.3gpp.org/news-events/2251-emmy_sa4 Accessed Apr 17, 2022.

of declared essential patents at ETSI. Their visualizations reveal how the number of patent families declared essential increases constantly over time, generation by generation. Their sample comprises 25,072 patent families disclosed at ETSI between 1994 and 2019, and their data suggests that during 1994–2000 (before the launch of 3G), the annual number of declared patent families was in the range of some dozens; it increased during 2001–2009 (after 3G launch and before 4G launch) to several hundreds, and, after 2009 (in the 4G era), to 1000–2000 patent families per year. In the most recent years, since 2017, the declarations have increased to several thousands per annum. The increasing trend in the number of patent declarations indicates an increasing number of technical inventions and is in line with the increasing innovation spawning characteristic of a GPT. However, it should be kept in mind that the quality of patented inventions may vary (Bekkers et al., 2020; Nagaoka et al., 2010).

Additional measures for innovation spawning in the context of cellular technology are the increasing number and variety of mobile apps in the smartphone era. The number of apps has grown exponentially, from some hundreds in 2008 to millions in 2022 (e.g., Gokgoz et al., 2021), and there are dozens of app categories classified by purpose, including apps related to photo and video, games, social networking, instant messaging, navigation, music, news, sports, health, travel, and education, to name a few. In particular, new innovations in gaming and emerging augmented and virtual reality (AR, VR) apps require enhanced broadband and lower latency, which illustrates how innovation spawning and improvement are intertwined characteristics of a GPT, enabling innovational complementarities within and between sectors (cf. Bresnahan, 2010; Knieps & Bauer, 2022). We may conclude, consistent with Proposition 2, that standardization and coopetition have been associated with innovation spawning and innovational complementarities in the context of cellular technology.

4.2.3. Pervasiveness

Pervasiveness can be measured in a variety of ways. Here we do not focus only on the original measure—that is, the number of application sectors (Bresnahan & Trajtenberg, 1995)—but rather on "pervasiveness in the aggregate" (Jovanovic & Rousseau, 2005) and technology diffusion to global geographical coverage. The former corresponds to the "many uses of technology," while the latter reflects that the technology is "widely used," following the distinction of Bekar et al. (2018). Fig. 6 Adapts the original illustration of Bresnahan and Trajtenberg (1995) to cellular technology and shows the increasing number of application sectors adopting it over time.

We use the level of global coopetition in standardization to assess the geographical coverage and partially also the relevant application areas. When assessing the role of standardization underlying pervasiveness of cellular technology, we can look at standardization coopetition in the 3GPP, including its global coverage. The 3GPP was set up in 1998 by an agreement including the working procedures between five actors from each ITU region, Europe, the USA and Japan and Korea, namely ETSI, T1, TTC, ARIB and TTA.[16] The working procedures define the role of the Partners (formal standardization organizations) and market representation partners (typically collaborative organizations of different types of companies). Furthermore, the liaison with other possible groups requires program co-ordination group (PCG, Group of the Partners) approval. Over the years the number of formal SDOs has increased and even more so the number of market representation partners[17] and liaisons to other groups.[18] These groups connect the 3GPP to all ITU regions and to specifically powerful countries like China and India, as well as to many actors in communications and automobile. The liaisons with over 60 ICT standardization and coordination groups enable global coopetition and innovation spawning far beyond that of the original mobile cellular communications sector (cf. Teubner et al., 2021).

Another way to look at pervasiveness is to examine the number of countries utilizing the 3GPP technology, including any or all of 3G to 5G technologies. There is global coverage information available at the GSM network operators' web site.[19] This gives qualitative information about the acceptance of the 3GPP standards and technologies worldwide. The availability of the 3GPP technology in a country, however, does not give quantitative information about the users. Regarding the evolution of the total market size, Fig. 7 illustrates how the number of mobile cellular subscribers has increased concurrently with the continuous standards development efforts in the 3GPP.[20] It is not easy to disentangle diffusion across application sectors since people have begun to use multiple mobile devices for communication in virtually all industries as the adoption of mobile phones has progressed.

Another measure for pervasiveness in the era of IoT would be the number of cellular IoT devices. Edquist et al. (2021) suggested that the number of cellular IoT devices has been increasing steeply and Park et al. (2019)(Park, Nam, & Kim, 2019) described the growing smart car market. These empirical observations are as well in line with Proposition 3: standardization and coopetition have been associated with pervasiveness of cellular technology.

[16] 3GPP1 TSG (Common meeting) Tdoc TSG#1(98)006; Source ARIB/ETSI/T1/TTA/TTC Title: 3GPP Working Procedures; https://www.3gpp.org/DynaReport/Meetings-SP.htm Accessed Feb 3, 2022.

[17] Partners and Market Representation Partners https://www.3gpp.org/about-3gpp/partners Accessed Feb 3, 2022.

[18] 3 GPP liaisons https://www.3gpp.org/about-3gpp/15-bodies-with-which-3gpp-has Accessed Feb 3, 2022.

[19] GSMA Network Coverage Maps https://www.gsma.com/coverage/Accessed Feb 3, 2022.

[20] https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx Accessed Jan 21, 2022. The path to this stage has required many steps, including regulation, spectrum auctions, etc., a detailed description of which is beyond this study.

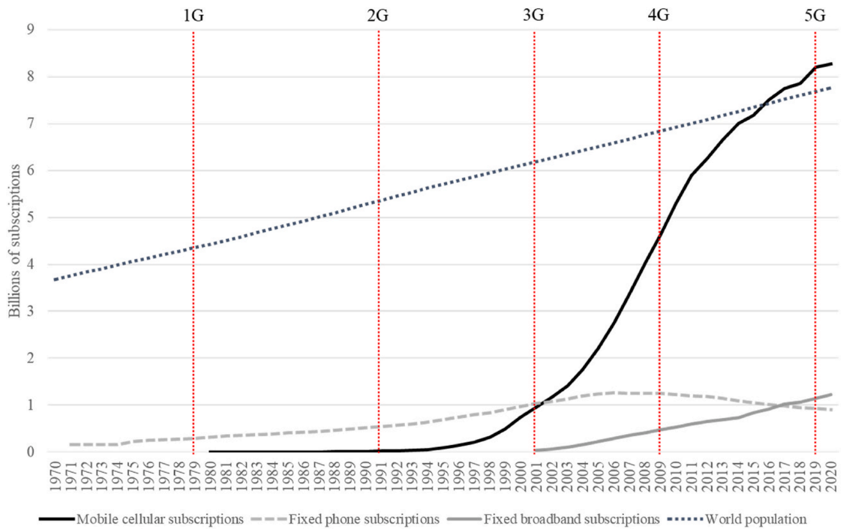

Fig. 7. Number of subscribers. Data source is World Bank (originally ITU). Mobile cellular: https://data.worldbank.org/indicator/IT.CEL.SETS, Fixed phone: https://data.worldbank.org/indicator/IT.MLT.MAIN Fixed broadband: https://data.worldbank.org/indicator/IT.NET.BBND Population: https://data.worldbank.org/indicator/SP.POP.TOTL Accessed Nov 9, 2022.

4.3. Summary

Table 1 summarizes the relationship between standardization and coopetition and their associations to the factors used to assess the nature of cellular technology as a GPT. We may conclude that standardization and coopetition have clearly been associated with the evolution of cellular technology and its GPT characteristics. Our observations are consistent with the Propositions 1, 2, and 3. Furthermore, the technological progress is not stopping: Currently, the next cellular technology generation, 6G, is under development (e.g., Ojutkangas et al., 2022; Yrjölä et al., 2022; Ziegler & Yrjölä, 2021). This suggests that standardization and coopetition may further promote improvement, innovation spawning, and pervasiveness of cellular technology.

In the early 2000s, Lindmark (2005, p. 52) noted that *"mobile data communications have not yet had any significant economic impact,"* which clearly is not the case anymore. We do not have a counterfactual world without standardization and coopetition related to cellular technology, so it is hard to identify and quantify accurately their causal impacts, including the effect on the rate and direction of technological progress. However, given the established GPT criteria—particularly the necessary conditions—the analysis suggests that cellular technology satisfies them, which is consistent with earlier analyses and anecdotal evidence. At a minimum, the role of standardization and coopetition ought not to be neglected when analyzing the evolution of GPTs, particularly in the ICT sector.

4.4. Limitations

Our framework and application are obviously not without limitations. First and foremost, while our analysis suggests the coexistence and coevolution of coopetition and standardization concurrently with strengthening GPT characteristics of cellular technology, we cannot make claims on the size of causal effects. Due to a missing counterfactual, we do not know what would have happened and what would have been the rate and direction of technological change in the absence of coopetition and standardization, including whether the impact on the extent and timing of innovation in both the GPT and the application sectors is suboptimal or delayed ("too little, too late," to use the jargon of Bresnahan & Trajtenberg, 1995, p. 106). Naturally, there are other confounding factors that have concurrently had both small and large impacts on the evolution of cellular technology, its improvement, and the enabling of innovations and pervasiveness. However, these confounding factors do not undermine the fact and key message of the article: that standardization and coopetition have been inherent in the evolution of cellular technology.

Second, we limited our attention to the "canonical" GPT criteria (Brynjolfsson et al., 2021) and did not consider extensively "other symptoms of a GPT" (incl. impacts on productivity, skill premiums, industry dynamics, stock prices, etc.), which Jovanovic and Rousseau (2005) analyzed in the case of electricity and IT.

Third, while briefly acknowledging, we did not analyze in detail the impact of regulatory regimes and public support on the evolution of GPT, while previous studies have noted the important role of regulatory regimes on the diffusion and evolution of cellular technology (e.g., 1G: Lyytinen & Fomin, 2002, pp. 2G–3G: Gandal et al., 2003; Kshetri et al. (2011); 4G: Forge & Bohlin, 2008, p. 5G: Robles-Carrillo, 2021; Bauer & Bohlin, 2022).

The presented framework is just one approach and could be replicated, elaborated, and improved further. The controversies of the existing GPT literature (e.g., Bekar et al., 2018; Vannuccini & Prytkova, 2021) are obviously a general challenge to any systematic analysis. For instance, the concept of pervasiveness could be extended to the analysis of how extensively the focal GPT impacts the key dimensions of peoples' wellbeing, as outlined in the Stiglitz et al., 2009: i. Material living standards (income, consumption, and

Table 1
Standardization, coopetition and GPT criteria related to the evolution of cellular technology.

Service Launch	Technology Generation	Key Releases	Coopetition	Improvements(Signature features)	Innovation spawning (OTT applications)	Pervasiveness (Global coverage)
1979 Japan	1G	NTT	National monopoly, contracted technology vendors	Mobile voice service	–	National
		NMT	Collaboration of national monopoly operators, vendors	Limited international roaming	Limited 1200/2400 modem enabled services, like fax	Limited International
1991 Finland	2G	ETSI GSM Phase 1	Collaboration of oligopoly operators and market driven technology providers.	Digital voice service		Limited regional
			Competition between regional SDOs	Text messaging, Regional (pan-European) roaming		Regional
	2.5G	ETSI GSM Phase2	Some SDO collaboration	EFR Voice codec, Circuit switched, Packet data	Email	International
2001 Japan	3G	3GPP Release 99	Collaboration of regional SDOs under ITU IMT umbrella, 3GPP established	AMR voice service, High speed data, Mobile terminal services and service capabilities	Browsing	Multi regional
		Release 5	3GPP collaboration with OMA, IETF	IP Multimedia Subsystem, HSDPA		
		Release 6	3GPP expanding and competing with 3GPP2	HSUPA, Extensions towards internet and broadcast	Streaming	
	3.5G	Release 7	TDD-SCDMA and WIMAX challenging the 3GPP FDD mainstream	HSPA, very high-speed data	Smart phone applications	
2009 Norway, Sweden	4G	Release 8	Global collaboration including many complementing forums	LTE and SAE, Mobile Broadband, Flat network (to follow Internet architecture)	Smart phone ecosystem	Global with gradual transition from 2G towards 4G
		Release 10	IMT Advanced	LTE Advanced	All web services	
		Release 13		LTE Unlicensed, Extensions towards machine to machine and location services	Machine to machine applications	
		Release 14		Extensions to mission critical and Internet of things services	Massive Internet of things applications	
2019 Korea	5G	Release 15	IMT 2020. However, global collaboration, regional trade politics become an issue	New Radio system, Ultra-Reliable Low Latency communication, mmWave	Any imaginable Internet based applications	Global without exceptions in technology
			First steps towards fragmentation in configurations	Support for Railways communications	Applications for other domains, like Railroads	
	5G phase 2	Release 16	Technology platform enables different configurations	NR Vx2 (*CP*-OFDM for SL), 5G radio for unlicensed spectrum, Extensions to private and government applications	Traffic and transportation, autonomous driving, Private and government services	
		Release 17		Enhanced Network slicing, positioning, URLLC. Support for non-telecom (non-terrestrial, satellite) networks	Industrial applications, robotics, manufacturing. Satellite	
		Release 18		Specific support of applications in multiple industry sectors		

wealth); ii. Health; ii. Education; iv. Personal activities including work; v. Political voice and governance; vi. Social connections and relationships; vii. Environment (present and future conditions); vii. Insecurity, of an economic as well as a physical nature.

5. Conclusions and implications

We have synthesized the intersection between standardization, coopetition, and GPT literatures to demonstrate that a standardization and coopetition perspective may add rigor to the empirical analysis and increase our understanding of the evolution of GPTs. We apply this framework to measuring whether cellular technology satisfies the established GPT criteria (esp. the necessary conditions) and provide suggestive empirical evidence on the role of standardization and coopetition in promoting the key GPT characteristics: improvement, innovation spawning, and pervasiveness.

Our analysis suggests that over the past thirty years, cellular technology has indeed become increasingly pervasive, has improved continuously, and keeps on spawning innovation in existing and new application sectors. Cellular technology indeed seems to increasingly fulfil the necessary conditions of a GPT. Furthermore, our observations illustrate how open, consensus-based standards development in the 3GPP has been associated with the evolution, development, and diffusion of global cellular technologies. The contributing firms have a dynamic coopetitive relationship: First, they collaborate in the development of global standards and compete in contributing the best technical solutions following the 3GPP working procedures, and second, they compete in the markets of the application sectors maintaining the achievements of collaboration based on the open standardized interfaces. To conclude, cellular technology provides an exemplar case on how standardization and coopetition are associated with the development of a GPT.

Despite the limitations of our framework and analysis, the findings nevertheless highlight that standardization and coopetition perspectives may have advantages compared to traditional GPT analyses and may increase our understanding of the technological progress and industry dynamics underlying the evolution of GPTs. Our observations have important implications for both future research and ICT policy.

First, existing and emerging standardization ecosystems are crucial to technological progress in ICT subfields, and neglecting these perspectives would lead to incomplete analyses and understanding. As currently AI (e.g., Trajtenberg, 2018; Brynjolfsson et al., 2021; Vannuccini & Prytkova, 2021) and blockchain (e.g., Ozcan and Unalan, 2020) are being discussed as new GPTs, future analyses of these ICT subfields could be more rigorous if their evolution were viewed from the perspective of standardization and coopetition.[21]

Second, from an ICT policy perspective, regulation, competition, and technology policies at different levels (national, regional, and international) necessarily have impacts on the development of technologies, coopetition, and interoperability. In the case of mobile communication, the critical decisions included the global spectrum policies, well-defined rules of oligopolistic competition, and a set of well-defined open interfaces to enable and even require collaboration, complemented by the rights of the consumers to make choices. Regulations and policies provide the rules of the game—that is, institutions (North, 1991) that for their part direct the rate and direction of technological progress of GPTs, including ICT. International coopetition between national and regional regulatory authorities has crucially impacted the development of global ICT ecosystems. While a detailed analysis of international strategic interaction, coordination, and coopetition among regulators was beyond the scope of the analysis here, their impact on the emergence, scaling, and evolution of standardized GPTs provides an interesting avenue for future research.

Third, spillovers and appropriability challenges are related to coopetition and standardization, as well as the development of GPTs. There is an emerging stream of literature discussing the challenges related to value appropriation in the context of standards and general-purpose technologies (e.g., Teece, 2018; Yang et al., 2022). Obviously, balanced rules of SDOs are crucial for companies to appropriate returns from their investments, provide incentives for adoption of the GPT and development of complementary innovations, and create incentives to participate in standards development. Therefore, policy makers and researchers should pay particular attention to the functioning of SDOs and that their rules of underlying coopetition are and remain balanced.

Fourth, the elaboration of the framework of coopetitive standardization of GPTs has important implications for the development of economic growth theories. Modern economic growth theory acknowledges that institutions are the most important factors impacting economic development (Acemoglu et al., 2005), and the ICT standardization ecosystem (and related regulations), with its formal and informal rules, can obviously be interpreted as such an institution. However, Schumpeterian growth theory (Aghion et al., 2016), which emphasizes the balance between innovations and competition, lacks ecosystem and coopetition perspectives. For instance, according to Aghion et al. (2016, p. 558), the Schumpeterian growth theory builds upon three main ideas: "(a) Long-run growth results from innovations; (b) innovations result from entrepreneurial investments that are themselves motivated by the prospects of monopoly rents; and (c) new innovations replace old technologies." As currently coopetition and standardization perspectives are missing, future research could try to incorporate them into the next generation of economic growth theory. This could increase our understanding on how an open, voluntary, and consensus-based standards development ecosystem contributes to technological progress, increasing standard of living, and human welfare.

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[21] See https://digital-strategy.ec.europa.eu/en/policies/blockchain-standards and https://www.iso.org/committee/6794475.html Accessed 17 Apr 2022.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.telpol.2022.102488.

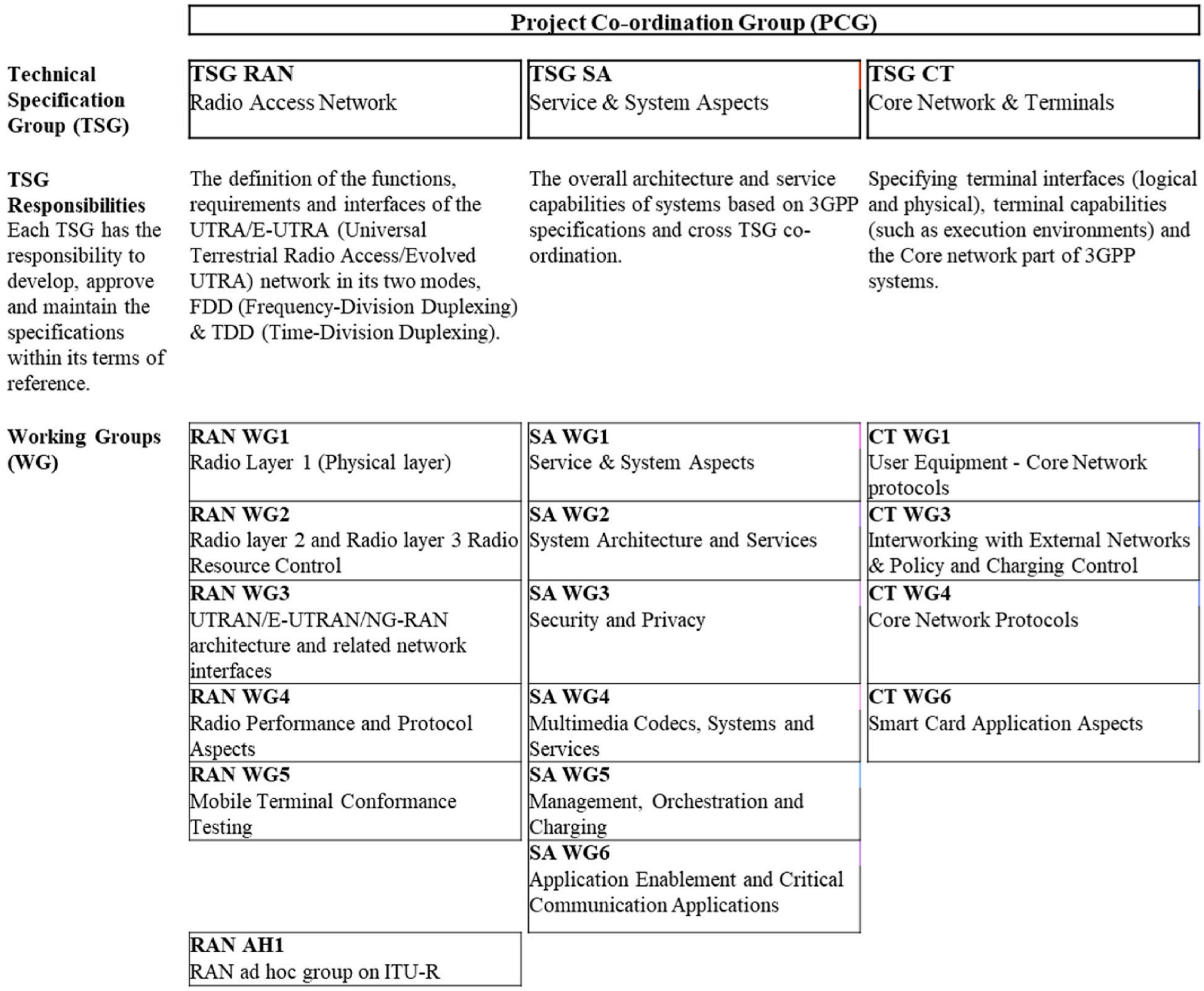

Fig. A.1. Organizational Structure of 3GPP. Source is https://www.3gpp.org/specifications-groups Accessed 21 Jun 2022

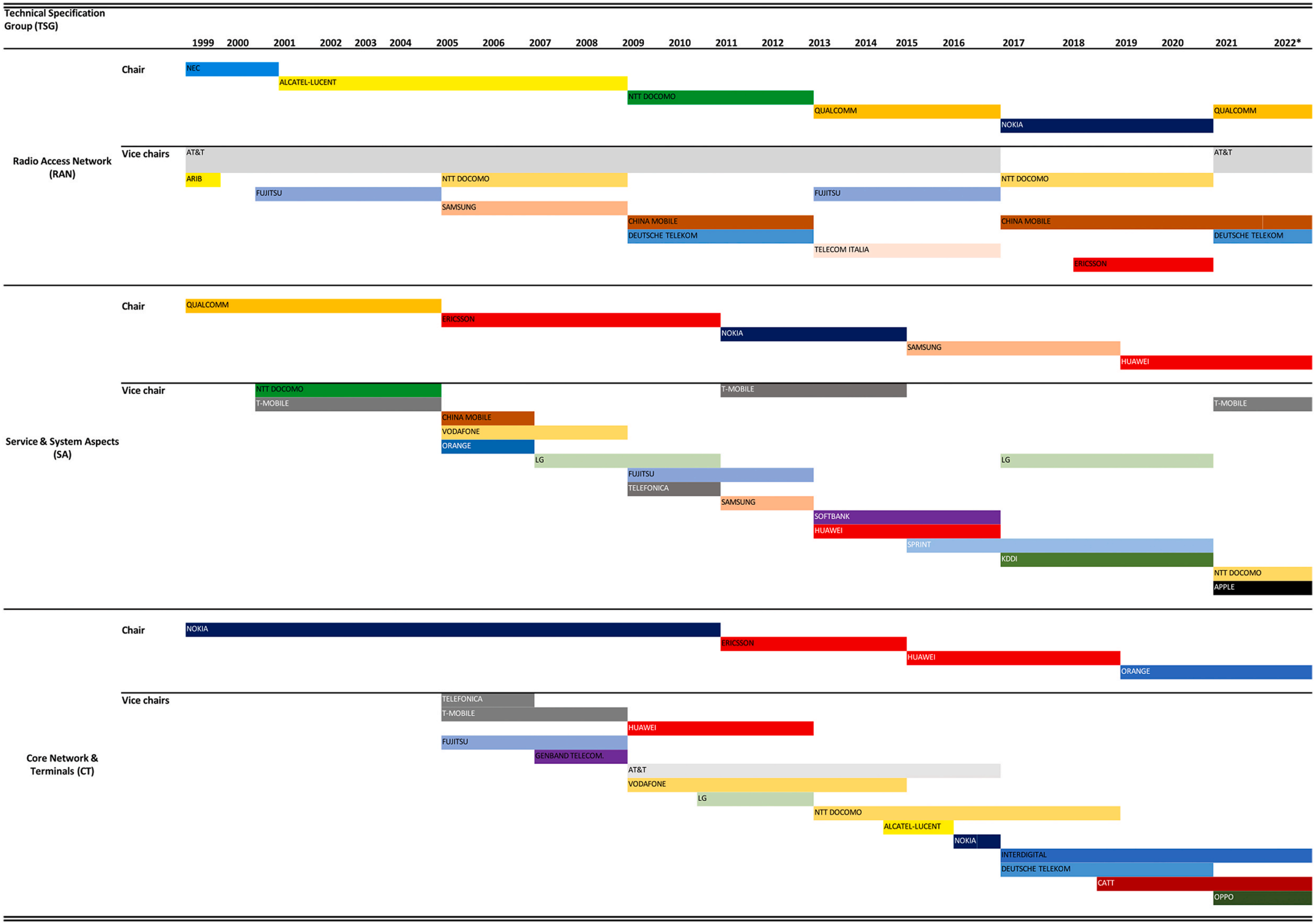

Fig. A.2. Organizations of chairs and vice-chairs of Technical Specification Groups Notes: Information collected from the webpage of 3GPP. RAN: https://www.3gpp.org/DynaReport/TSG-WG–RP–officialsHistory.htm; SA: https://www.3gpp.org/DynaReport/TSG-WG–SP–officialsHistory.htm; CT: https://www.3gpp.org/DynaReport/TSG-WG–CP–officialsHistory.htm Accessed 21 Jun 2022, updated 6 Nov 2022.

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