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Less Revolution, More Evolution: Competitive Markets, Copper-based Broadband Tech, and Lessons for the Future

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***Abstract*— This paper examines the factors that led to the ascendence of copper-based broadband technologies for delivering Internet connectivity in the United Kingdom. The outcome for competing fixed-line technologies such as coaxial cable and optical fibre is considered in conjunction with the role played by strategic and policy choices of regulators and a nascent competition in the telecom market. The paper shows that the deployment of copper-based broadband technologies was highly contingent on political expediency, uncertainty surrounding the potential end-user adoption of Internet connectivity, the fragmented nature of infrastructure development post-privatization, and commercial imperatives for British Telecom as competitive market forces took hold. The paper correlates these developments with the nascent digital transformation of telecom industry through software-defined networks, network function virtualization, and open radio access network technologies. The paper highlights that due to the inherently capital-intensive nature of the telecom industry and the role of end-user demand in competitive markets, the paradigmatic change offered by fibre technologies, or digital transformation of access network infrastructure will be a long-term prospect rather than a near-term outcome.**

***Index Terms*—Broadband technologies, Competitive markets, Economics of infrastructure investment, Evolution of telecom business, NFV, Open RAN, Optical fibre, Regulatory policy, SDN, Telecom futures**

Introduction

This paper examines the factors leading to the widespread adoption of copper-based broadband technologies (DSL and its variants) in the United Kingdom (UK) around the turn of the millennium. The UK was not alone in adopting DSL to satisfy the growing demand for Internet connectivity; but its adoption in the UK richly illuminates – in the words of this special issue's call for papers – the "interplay between technologies and designs on one hand and societal, economic, and regulatory factors on the other". We reflect on this interplay in some views on current developments related to the digital transformation of the access network infrastructure towards the end of the paper.

Within the telecommunications industry, the provision of non-voice services was assumed to be the industry's destiny throughout the 1970s and 1980s, pre-dating the widespread adoption of the Internet. In the UK, these factors formed a context in which DSL leapfrogged over longer-established technologies (such as dial-up, cable, fibre, and integrated services digital network i.e. ISDN) which had long been considered the most appropriate technologies for delivery of non-voice services to end-users. Insights from this story feed into our reflections on current and projected developments related to software-defined network (SDN), network function virtualization (NFV), and open radio access network (RAN) technologies. Where relevant, the paper covers these technology developments and network transformations in the global context, with the UK and other comparable regional/national economies as the main examples.

DSL stands for digital subscriber line. It enables the delivery of broadband over the copper local loop [1]. The copper local loop is the pair of copper wires initially installed to deliver analogue telephony to the end-user premises. In DSL, the copper loop requires no modification although new equipment is needed at the exchange. The preservation of the unmodified local loop turned out to be an important point in DSL's favour as the demand for broadband connectivity grew.

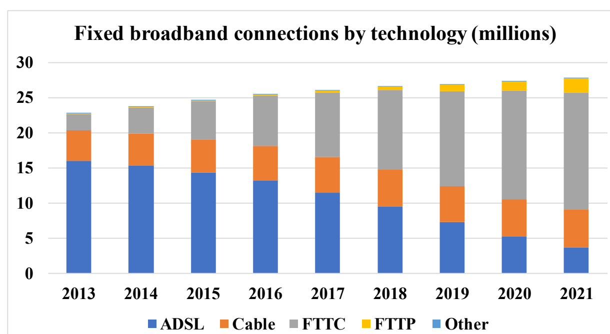

Fig. 1. Broadband technology market share in the UK

For a late entrant on to the broadband scene, DSL has enjoyed remarkable success and longevity. As of 2021 (see Figure 1), 74% of fixed-line connections to end-users in the UK were met by DSL-based technologies, four-fifths of which were fibre to the cabinet (FTTC), in which a form of very-high-speed DSL (VDSL2) is used over the short length of copper loop from the cabinet to the end-users' premises. Cable delivery counted

*This paragraph of the first footnote will contain the date on which you submitted your paper for review, which is populated by IEEE.

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for only 19% of fixed-line connections. Fibre to the premises (FTTP or full fibre), which appears to be universally accepted as technically the best medium, accounted for only 7% of fixed-line connections, although the growth of FTTC means that fibre is creeping ever closer to the end-user [2]. To appreciate how DSL became and remains dominant in the UK, we need to look at the country's regulatory history of telecommunications.

Privatization of the UK Telecom Industry

The 1980s saw the transition of the UK's national telecommunications operator British Telecom (rebranded to BT) from a public-sector monopoly to a privatized company. To counteract the privatized BT's monopoly of telecommunications, the UK government licensed a competing telecom operator, Mercury. The British Government also created the Office of Telecommunications (Oftel), a regulatory body for telecommunications industry. The UK cable industry was not seen as part of the telecommunications industry and therefore regulated by a different body, the Cable Authority (CA).

To ensure a competitive market that offered choice to the end-users, two key regulatory policies were adopted: price control (Oftel) and infrastructure competition (both Oftel and CA). Oftel's approach regarding price control was to limit BT's earnings via a formula based on the retail price index (RPI). Designated RPI-X, BT was required to price its products a certain percentage (X) below the RPI, with the value of X being periodically revised by Oftel. A consequence of the RPI-X formula was to restrict the profitability of both BT and Mercury (as Mercury priced its products competitively with those of BT).

To encourage infrastructure investment, Oftel and CA mandated Mercury and the cable operators to build their own network infrastructure. For the 'last mile' access to end-users Mercury initially relied heavily on BT's local loops via interconnect agreements. Thus the existing copper local loop remained a key asset, capable of being leased to a competing operator for whom installing a replacement would have been unviable.

From a technical point of view, cable was considerably more advanced than anything else available to residential end-users at the time. As part of the Cable and Broadcasting Act 1984, the cable operators' networks needed to be able to carry sixteen 8 MHz-wide video channels simultaneously, and be capable of delivering video to 10,000 or more dwellings simultaneously. As a result, the cable networks were capable of delivering bandwidths of 1.445 Mbit/s for voice and video content as of the mid-1980s. To ensure that the cable operators developed as a strong alternative to BT, an embargo was placed on BT delivering broadcast content. This deterred BT from deploying fibre in its access network (the part of the network that connects to end-users' premises), although BT had been deploying fibre in its core network for some time. BT was permitted to bid for up to one-third of the cable franchises, and although it invested in some cable franchises during the mid-to-late 1980s, it exited cable television business in 1990-91 after deciding it was not profitable. Cable infrastructure therefore remained firmly in the hands of 'traditional' operators.

The cable operators, then, ought to have been well placed to provide high capacity fixed-line connections to residential end-users during the 1980s. However, cable adoption in the UK lagged other countries. The USA, for example, had a long tradition of cable TV starting with late 1940s and reportedly had nearly 40 million subscribers by mid-1980s. A hindrance to the wider adoption of cable in the UK was the government's decision that cable franchises would be allocated as regional monopolies (via the CA) resulting in network fragmentation. Although each operator was required to deliver local content, until the late 1980s some cable operators only provided the terrestrial television channels, for which the majority of the population already had access via conventional television broadcasting [3]. Due to the lack of added-value content, cable was perceived as "down-market" and struggled to achieve significant market penetration [4]. Many operators did not pursue telephony seriously at an early stage. Although the cable operators began to merge operations by late 1980s to grow end-user reach and to gain economies of scale, a sizeable number of neighbouring networks were often mutually incompatible at the technical level, thereby increasing the costs of network consolidation.

Non-voice Services and Contending Technologies

During 1970s and 1980s the telecommunications and cable industry had begun to explore non-voice services such as videophone (e.g. Picturephone, AT&T USA), teletext, interactive videotex (e.g. Minitel, France Télécom; and Prestel, BT), and video-on-demand to generate new revenue streams. Therefore, although BT concluded that installing fibre in the access network was commercially unviable due it being restricted from delivering broadcast television, it continued to test other technologies such as ISDN and broadband ISDN (B-ISDN) to deliver non-voice services. The ISDN set of standards, protocols, and technologies were developed by the International Telegraph and Telephone Consultative Committee (Comité Consultatif International Téléphonique et Télégraphique i.e. CCITT) and European Telecommunications Standards Institute (ETSI) as part of a 4-year cycle. Although conceptualized as early as 1971, ISDN's technical recommendations were not approved until the end of 1984. Consequently, applications and services that used ISDN's capacity remained underdeveloped.

Installation of ISDN was labour intensive, time consuming, and expensive due to the high cost of network equipment required for it. The privatized BT were unsure whether end-users would pay the deployment cost. In contrast, due to state ownership of Deutsche Bundespost (Deutsche Telekom's predecessor), end-user's willingness to pay was not a significant constraint in Germany. ISDN was widely deployed there in late 1980s and early 1990s, and saw significantly higher adoption from residential end-users.

By the mid-to-late 1980s, BT and incumbent telcos in other countries began to realise that ISDN's bandwidth of 128 kbit/s was insufficient for voice, data and video services [5]. In response, B-ISDN was initiated by Broad-Band Task Group (BBTG) of the CCITT to deliver a high-bandwidth "killer application" and to generate a significant revenue stream. In parallel with B-ISDN development, another group of researchers began to consider other ways to improve on the initial ISDN specification leading to the development of DSL.

As with B-ISDN, the capability to deliver video (specifically video-on-demand) was a principal driver of DSL research. This research focused on the unmodified copper twisted-pair telephone line. An early concept definition of DSL, high-bit-rate DSL (HDSL), was developed in late 1986 at AT&T Bell Laboratories and Bellcore in the USA. Like ISDN, HDSL also enabled symmetric traffic i.e., the same bandwidth upstream and downstream. Given the incumbent telcos' goal of delivering video-on-demand and other non-voice services to residential end-users, increasing downstream traffic bandwidth capabilities of HDSL became a key priority. In response to this, asymmetric DSL (ADSL) technology, which promised up to 7 Mbit/s for downstream traffic and 1 Mbit/s upstream traffic, began to be developed at Stanford University and AT&T Bell Labs in 1990 [1]. In contrast to ISDN and B-ISDN, DSL retained the analogue transmission of voice in a frequency band from 0 to approximately 4 kHz, reserving the transmission of data to higher frequency bands on the same line. DSL required the end-user to fit a filter at their premises to reduce interference between voice and data channels [1]. Since most end-users could fit the filter by themselves the cost, engineering effort and time required to deploy DSL was greatly reduced compared with ISDN or B-ISDN. These advantages proved crucial in the commercially challenging environment BT faced in late 1990s.

DUOPOLY REVIEW

In 1991 the British government conducted a review of BT and Mercury's duopoly and further liberalized the market. Although BT was allowed to deliver on-demand services from 1993, it continued to be prohibited from delivering television content (a prohibition that remained until 1999) so that cable operators could retain their unique selling proposition and extend their infrastructure deployment. Oftel also continued its policy of price control. BT's deployment of fibre therefore remained focused on the core network throughout the 1990s due to the perceived lack of commercially viable high-bandwidth applications. BT's strategy was to protect its UK market share and its revenues from telephony, and to expand its footprint abroad to counter the perceived threat from US and Europe-based operators investing in the UK.

At around the time of the duopoly review, the woes of the financially embattled and fragmented cable industry were augmented by the emergence of satellite broadcasting in the form of the British Sky Broadcasting (BSkyB) Corporation. The satellite broadcaster's reach quickly dwarfed the number of end-users that the fragmented cable industry could reach, offering the satellite broadcaster economies of scale unavailable to cable operators. As a result, the cable industry lost out in the bidding war for films and sports (notably the newly created premier league for soccer/football). To solve the content issue, cable operators had to buy content from BSkyB. In addition, they relied on BT (or sometimes Mercury) to deliver telephony services outside their franchise areas. Thus, although the cable operators could potentially deliver integrated telephony and television, they led in neither of these market segments. Infrastructure investment stalled, and by the early 2000s, the cable infrastructure could reach only 50% of the UK premises compared to the near-universal UK reach of BT.

By 1999, the market sentiment that had favoured international expansion began to change, affecting not only BT but also other operators such as AT&T, MCI, and Worldcom (culminating in the telecom crash of 2001). In the financial year 1998-99, the losses from BT's joint ventures grew to £342M. By March 2000, BT's net debt had grown to £8,700M. It was in this context that the UK's insufficient investment in high-bandwidth access infrastructure became highly apparent as the end-user demand for the Internet and Web grew rapidly.

EMERGENCE OF THE INTERNET AND WEB

The emergence and adoption of the Internet and Web was largely unforeseen because of its origins as a network of networks for academic institutions. Initially residential end-users' Internet access was supplied through dial-up modems, which relied on existing Public Switched Telephone Network (PSTN) connectivity to carry data via a modulated audio signal in the voice channel. While a dial-up modem was in use, the end-user could not make or receive telephone calls. Furthermore, a dial-up modem was limited to 56 kbit/s. By the mid-to-late 1990s, dial-up connectivity was proving inadequate. The cable operators, consolidated into mainly Comcast, NTL, and Telewest by the late 1990s, attempted to address this gap in the market with cable modems, which were able to use spare capacity on the cable network to deliver data. With the Data Over Cable Service Interface Specification (DOCSIS) 1.x standards, released from 1997 onwards, cable could deliver bandwidths of up to 13 Mbit/s. However, due to the fragmented nature of cable-network deployment in the UK some cable franchise areas lacked the capability to carry data in the upstream direction (that is, from the end-users' premises to the nearest cable plant). Thus, of the 13.3M UK homes served by cable, only around 8.8M homes could receive broadband via cable [6]. In contrast, cable operators in the USA, Germany, and France had more extensive networks with upstream capabilities, and were better positioned to capitalise on the demand for the Internet and Web.

In the interim, the adoption of B-ISDN and the deployment of fibre in the access network also failed to progress. Deployment of fibre in the access network had stalled in the absence of what BT saw as revenue-making opportunities. B-ISDN suffered from the lengthy negotiation of technical standards and long development cycles of four years that had plagued ISDN development. Crucially B-ISDN relied on asynchronous transfer mode (ATM), a cell-based switching technology which required a virtual circuit to be established between two end points (i.e. it was connection-orientated), and was therefore time-consuming and expensive to install. The open nature of standards such as Transmission Control Protocol (TCP), Internet Protocol (IP, which was not connection-orientated), and Ethernet, which formed the basis of the Internet, meant that equipment based on them could achieve considerable economies of scale compared with ATM-based equipment. With the growth of Internet and Web traffic, the telcos were on the lookout for technological solutions that could deliver high-bandwidth capacity quickly and at low equipment cost. This was the context in which DSL emerged as the only plausible option in the UK.

EMERGENCE OF DSL

Following the development of early prototypes of HDSL in 1989, trials and testing of DSL variants had continued throughout the 1990s with a view to providing not only video-on-demand capability but also additional services to PSTN operators. Although DSL's bandwidth declined with increasing distance of the end-user from the local exchange, one of DSL's main advantages was that it did not require extensive modification of the local loop (unlike ISDN or B-ISDN). Although DSL was originally devised for video-on-demand services, it could be adapted for general broadband use based on IP. Notably, both video-on-demand and residential Internet traffic had an asymmetric traffic pattern, with downstream traffic considerably exceeding upstream traffic. This asymmetry suited DSL as it reduced the crosstalk problems that it was prone to, allowing the first iterations of ADSL to offer respectable downstream speeds – except for end-users living a long way from the exchange.

Despite the benefits of ADSL, the dial-up modem had important advantages which kept it in contention for some time. Compared to ADSL, dial-up was ubiquitous, cost less, and was easier to install than the then nascent DSL technology. As a result, even by 2001-2002, of the 12M premises connected to the Internet in the UK, only 100,000 were on DSL and 96,000 were on cable modems [7]. The remaining premises were connected via dial-up modems. However, the growth in Internet traffic had clearly outpaced the capabilities of dial-up modems. ADSL provided what at the time might have been thought of as a good interim technology, allowing the incumbent operators (such as BT) to maximise returns on their existing copper assets. However, higher-speed variants of DSL, notably forms of VDSL, were already well under development, so there was an upgrade path available, albeit one that would require the installation of neighbourhood cabinets with fibre connections back to the exchange. Even the expense of installing these cabinets was considerably less than that of laying fibre to individual homes. Finally, DSL in all varieties benefits from the local loop being a point-to-point connection, unshared with any other end-user. This distinguishes it from both cable and GPON (the passive optical network service that BT offers), in which the access infrastructure is shared by several end-users, resulting in data rates that often do not reach the maximum speeds promised in advertisements.

Optical fibre technologies (used in conjunction with coaxial cable) held significant technical advantages over copper-based DSL technologies, but the deployment of optical fibre has been gradual and highly incremental, guided by the role of cost of deployment and end-user demand rather than technical merit. With this insight in mind, we offer some reflections on current developments related to digital transformation of the access network infrastructure.

PARALLELS TO PRESENT DAY DIGITAL TRANSFORMATION OF ACCESS INFRASTRUCTURE

Two technological developments expected to play an important role in the digital transformation of the access network infrastructure are virtualization and open radio access network (RAN). Of these, virtualization through the use of software-defined networks (SDNs) and network function virtualization (NFV) offers a technological solution that can reduce network architecture complexity, lower network-related expenditures, and enable operators to innovate faster (since it makes operators less dependent on standards development organizations and hardware vendors) [8] [9]. Open RAN solutions offer the opportunity for mobile operators to lower capital expense by disaggregating general-purpose hardware and software for base station deployment. Base station hardware can be deployed with open source, virtualized radio units, potentially reducing vendor lock-in through increased competition in the supply-side of cellular infrastructure providers [10] [11].

In principle, done at a scale with a focus on interoperable low-cost, white-labelled hardware, SDN, NFV, and open RAN offer the prospect of reduced barriers to entry for new operators and increased competition on the supply side, and could incentivise operators to innovate faster at least to control capital and operational expenditures [12]. Such optimistic projections of SDN, NFV, and open RAN however overlook the challenges facing the operators and the role of existing, legacy infrastructure in their decision-making.

NFV, besides facilitating the deployment of general purpose hardware, also increases the prospect of technology companies such as Amazon, Microsoft, and Google, with well-established expertise in high-volume cloud- and data-centre-based server operations, offering telecommunications services. Although any such new entrants are likely to rely on incumbent network operators to access the network, resulting increased competition in services may lower the average revenue earned by the incumbents per end-user. SDN enables network operators to share the physical grid, increasing economies of scale and reducing duplication in physical infrastructure (in particular the access network). Both NFV and SDN could create increased reliance on software to manage hardware assets resulting in consolidation of network infrastructure. Such a scenario also increases the likelihood of intervention by competition and regulatory authorities [9].

As a result of these uncertainties, although several operators have invested in SDN/NFV-based transformations, their approach varies significantly (see [8]). For example, AT&T (USA) and Telefónica (Spain/Europe) appear focused on SDN-based network-on-demand deployments and open NFV standards for voice and data processing and switching covering business and residential end-users. Vodafone (UK/Europe) and SingTel (Singapore) have pivoted to cloud-based services with a gradual SDN adoption roadmap for the businesses. BT appears to be leveraging its strengths in wholesale network infrastructure provision in the UK to roll out NFV-based virtualization of network functions and virtual customer premise equipment to other operators.

Although open RAN enables white-labelled commoditized hardware to run base stations, heterogeneity in the network raises challenges in terms of patching security flaws, risks of multi-vendor maintenance contracts, and the need for in-house hardware-management expertise [10]. Whether open RAN can deliver industry-standards-based hardware and benefits proportionate to costs remains unclear [13]. As a result, most of the high-profile open RAN deployments so far (late 2022) appear to have been by Rakuten (Japan) which is a new entrant to the Japanese market [14]. Pilot/greenfield deployments by established operators such as Vodafone (UK/Europe) and Etisalat (United Arab Emirates) appear to be the other notable examples.

Discussion and Conclusions

As the historical part of this paper shows, DSL was taken up for fixed-line residential broadband deployment in a context where cable (a technically superior means of delivering data) had not made the inroads into the UK market that the investors had expected, and where BT had historically focused its fibre deployment in the UK on its core network. The key to understanding such an outcome lies in two narrative threads - the contending technologies and the strategies adopted by the various market players.

Throughout the 1980s and 1990s, the technologies being developed institutionally to deliver high data-rate services (including video) were themselves developed prior to any clear market demand. ISDN, and DSL belonged to this category. As the narrative shows, DSL was largely an unheralded option for most of the 1990s. In the 1980s ISDN was the front-runner, with broadband ISDN and fibre considered the optimal long-term solutions. The emergence of DSL as a favoured technology was contingent on a number of factors in which its lower cost of deployment and prevailing market conditions were key contributing factors.

The backdrop to these events was principally the privatization of BT, increased competition in the markets, and the way the telecommunications industry was regulated. Both Oftel and the CA attempted to encourage infrastructure competition as a means of reducing BT's market power and its advantages as a former monopoly. However, the inability of the cable industry and the new telephony companies to develop as effective alternatives meant that BT functioned as a quasi-monopoly, with significant power in a number of market segments including wholesale network provision. The institutional focus on competition therefore led the market from a BT monopoly to a weak oligopoly with BT, Mercury, Sky, and cable operators occupying different segments of the communications market by the end of 1990s. This meant that although BT's market influence changed due to regulatory policies, the alternatives that had emerged (Mercury and the cable operators) failed to develop as effective competition to BT.

For the regulators, a principal objective was to prevent BT from misusing its advantage, which they did by capping its prices. However, this strategy had unintended consequences, and, along with other policies, led to underinvestment by BT in its infrastructure. Ironically, with the cable industry, policies that were intended to promote investment in infrastructure proved counter-productive in the long term because of the regional organization of cable franchises. Both outcomes highlight the manner in which historically contingent policy and strategy decisions led to DSL emerging as the technology of choice for high-bandwidth (broadband) connectivity.

Until the unexpected emergence of the Internet and Web, most of the key market players envisaged high-bandwidth technologies as the means by which they themselves would deliver video-on-demand. Indeed video delivery was seen as the main service that would power high-bandwidth residential connectivity and related monetization strategies. Interactive videotex, video-telephony ventures by the incumbent telcos, and video-on-demand ventures by the cable operators are emblematic of the belief of the operators such as BT, Sky, NTL, and Telewest that video delivery presented the opportunity to grow revenue, expand their end-user base, and capture a potentially lucrative new market area before it became price-competitive.

Underlying all these issues is the fact that the nature of telecommunications changed from the mid-1990s in ways that were unpredictable at the time of privatization, and which could not easily be accommodated within the structures set up on privatization. Not only did the end-users seek a high data-rate IP-connection, but the congruence between the physical network and the services delivered became weaker, so that an IP-based service could be delivered over several types of physical infrastructure, such as cable, telephone, fibre, etc. Telephone and cable, although regulated by different bodies, were complementary and competitive at the same time.

The unexpected popularity of the Internet and Web, and the high number of dial-up subscribers, suggested there was an end-user demand for better speeds and bandwidths. It also opened up the possibility of a market keen to adopt new technologies that delivered such speeds. However, the rise in Internet and Web usage had caught the operators off guard, although all had prior reasons to be interested in delivering high-bandwidth services to end-users. Cable operators were still struggling to gain a foothold, and BT, the largest telecom operator, lacked the requisite financial resources and the technological capacity. As a result, the prevailing economic climate, regulatory rules, and fragmented competition did not favour extensive investment on the part of the operators. BT chose to adapt the available copper network footprint and go with the less expensive and commercially expedient DSL technology, previously developed for video-on-demand delivery as it allowed BT to sweat its copper assets. This highlights the difficulty for telcos like BT of making any significant infrastructure investment given the prevailing economic environment and market conditions. Neither a command economy nor a deregulated, liberalized competitive market could have led to the technologically best configured solution in such a situation. Although in hindsight the selection of DSL may seem like an obvious choice, as the discussion in this paper shows, at that time it was unforeseen, dependent on commercial expediency, and historically contingent.

DSL's success and the longevity of the underlying copper-based network infrastructure also offers some lessons for the future when prevalent models of competition in telecoms sectors in most high- and medium-income countries are considered. In network industries where the regulatory impulse is to let the market compete and make the decisions about the products and services on offer, technological merits or capabilities, although influential, are only one of the factors that determine the adoption of the technologies. Thus although technologies such as SDN, NFV, and open RAN could potentially revolutionize the operation of access-network infrastructure, their actual deployment is likely to be contingent upon multiple factors among which may be cited: the need to co-exist and interoperate with legacy technologies, market forces, cost constraints, and potential regulatory oversight. Moreover, any deployments must yield returns on investment, both short-term and long-term, in terms of reduced cost of operations, increased end-user retention, and increased revenue.

Due to the inherently capital-intensive nature of the physical infrastructure in the telecom business, decisions on technology adoption and deployment will probably continue to be based on end-user demand, on whether the technologies serve the perceived market needs, and on whether such investments align with the strategic interests of the industry players. For example, although SDN/NFV offer new entrants the opportunity to deliver service differentiation, most new business models have to rely on access to existing network infrastructure. Any new entrants need to cooperate and compete with the incumbent network operators. Similarly with the exception of greenfield deployments, any open RAN deployments by incumbent operators will need to work with existing, proprietary base station cellular network equipment.

In a competitive market, the incumbent industry players, i.e. network providers or service providers, are almost certain to be accountable to their shareholders and therefore will have a fiduciary duty to "sweat the assets" before embarking on any ambitious overhaul of their businesses. Consequently, however innovative proposed upgrades to physical fixed-line or wireless infrastructure may be (possibly through the deployment of optical fibre, 5G, or 6G, or the digital transformation of fixed-line and wireless access infrastructure through virtualization, SDN, NFV, or open RAN), innovation by itself is unlikely to be sufficient justification for their adoption, as we have indicated above. Innovative technologies are often spoken of in popular discourse as harbingers of paradigmatic societal change. Although such discourse is usually well-intentioned, any revolutionary changes in the telecoms sector need to be grounded in the recognition of the role of existing physical capital, the dynamics of end-user demand, and the need for "killer applications" that justify the financial investment. If the snapshot of history covered in this paper is any indication, taking a long-term view of costs, investments, and benefits will remain the norm amongst the incumbent industry players. An exception to this norm is likely to be a new market entrant that not only has access to very long-term investment capabilities but also does not have any legacy physical network asset liabilities. For those already in the telecom business however, "less revolution, more evolution" will be the mantra in the near- and long-term future.

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