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Review

Living and Fluid Networks: The way ahead?

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ABSTRACT

The Internet is arguably the most complex infrastructure created by humankind. It is constantly and rapidly evolving to satisfy increasingly important and diverse requirements. Its underlying *network infrastructure* is experiencing a mutation from a transport-only, data-less, dumb infrastructure to a multifaceted and distributed system mimicking a *living* being and consisting of a stratum of *fluidified* networking and computing resources, dynamically organized and managed by more and more intelligent and autonomous algorithms, which generate and exploit increasing quantities of data, and provide customized services and applications alike everywhere. In this position paper, after a very brief historical excursus of how networks have evolved so far, we postulate that the recent advances in terms of networking technologies and their programmability improvements may provide the foundation of a future Internet where not only netputing (i.e., networking and in-network processing) services will be deployed on the fly, but even the protocols themselves that rule the Internet's operation will be dynamically adapted to the context and the needs of services and applications. Data and intelligent algorithms will be used not only to deliver personalized applications, but also to better operate the network itself. This also means that applications will be more deeply rooted within the network, so as to provide adaptive features, tailored to user needs, capable to better exploit network-generated data and functionality and to be (dynamically) instantiated (close to) where they are needed. The network will become even more pervasive and more integrated, further absorbing residual conceptual differences, e.g., between cellular/mobile and wired/core sections. Unlike for early attempts made, e.g., by active networking in the 90'ies, the time has probably now come for such a revolution.

1. Introduction

More than 50 years ago, when the basic principles that led to the Internet were first conceived, nobody could have imagined how they would change our life. Even if we put aside the Internet's face of a "global information system" [1], and we just restrict our analysis – for the purpose of this paper – on the Internet as a "network infrastructure", we can see impressive changes over time in both requirements and usage patterns.

For sure, physical connectivity supporting a transparent transfer of information is not any more the only functionality required from the network. Intelligent algorithms and features are needed to make the network able to adapt and evolve, to meet changing requirements and scenarios and to provide tailored services to users. Data generated by the network and by the users need to be exploited by the network itself and to be capitalized outside the network.

With this position paper, we postulate that the time has come for the Internet not only to change our own lives, but also to autonomously change itself. Indeed, the increasing pervasiveness of artificial intelligence approaches, combined with the modularization and the "fluidification" of computing and networking building blocks, brought about by modern programmable networking trends, makes us imagine the emergence of a new breed of network architectures, with an unprecedented ability to (autonomously) change, so as to best adapt to context, and that we will call ***Living and Fluid Networks***.

We are certainly not the first to believe in such a future evolution, whose roots possibly date back to as much as more than 20 years ago, with, on the one side, pioneering active networking proposals [2], and on the other side the vision to combine cognition loops [3] into networking [4]. However, we believe that now time is mature for a shift towards an Internet infrastructure which will not only provide support for connectivity and data delivery, but will also include the tools for adapting its operation to the changing contexts and service needs, and thus "re-engineer" itself. Tools which may ultimately even evolve into a (not-too-science-fictionary!) "living" Internet, gradually capable to take more and more autonomous adaptation decisions. Key to this evolution is the availability of: (i) better underlying technologies, drastically improving communication and computing performance; (ii) new techniques for network softwarization and related primitives and interfaces; (iii) intelligent and autonomous algorithms; (iv) data about the network, service and user behavior; (v) applications integrated with the network, performing in part also networking functionality and customized to user needs. The network will be also more pervasive and more integrated, further absorbing residual conceptual differences, e.g.,

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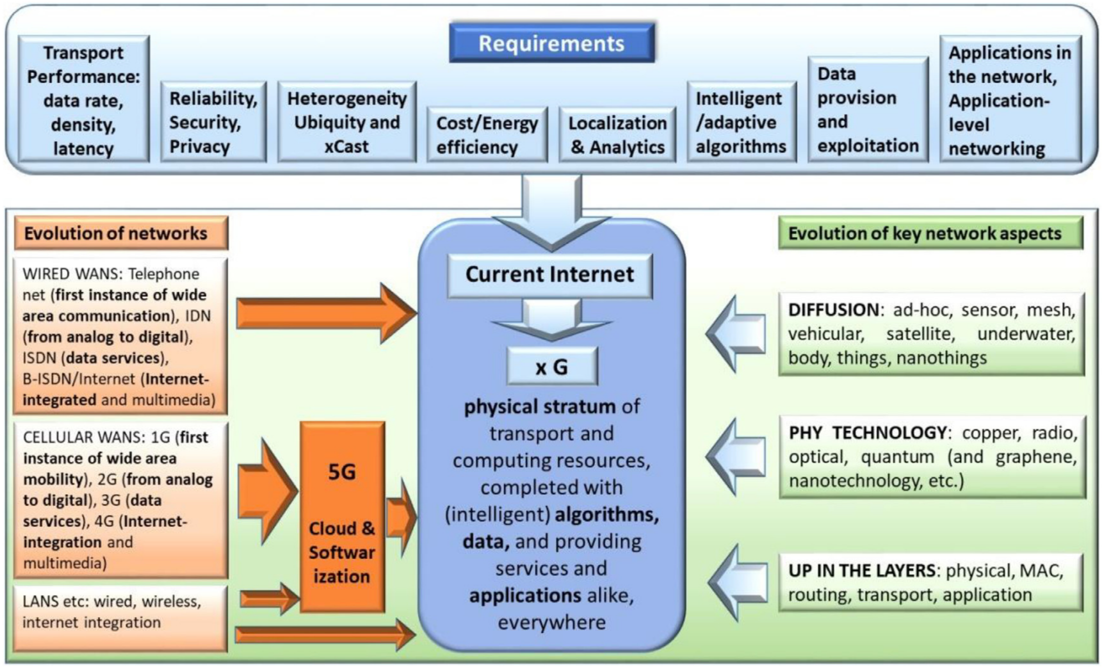

Fig. 1. Overall picture of the evolution of networks.

between cellular/mobile and wired/core sections.

This paper is very simply organized in three sections focusing on past, present and possible future of the network infrastructure. Through the paper we will make reference to Fig. 1, which cursorily summarizes: (i) how networks developed and evolved (left side of the figure); (ii) past and current main trends behind such progresses (right side of the figure); (iii) traditional and new requirements (upper side of the figure) that should be satisfied by the future instance of the network, which we call xG, just for the sake of having a neutral future-proof placeholder name (as opposed to "future", "evolved", etc.) and also because a softwarized network will evolve more rapidly and incrementally with new software releases, rather than with major generational leaps.

2. A look to the past

As shown in Fig. 1 (left-hand side), networks have been traditionally designed and standardized as independent silos.

Wired Wide Area Networks (WANs) started as the plain old telephone system, evolved into the Integrated Digital Network (substituting analogue with digital technologies), tried to integrate services (ISDN) and improve performance (B-ISDN), but failed due to the perhaps not fully expected deployment of the Internet in the early nineties; the aftermath is that technologies such as the Asynchronous Transfer Mode, meant to become "universal", became just another component of the growing Internet before disappearing.

Cellular WANs took a completely independent evolution path. The first analog generation (1G) made a first giant leap when it was replaced by the digital GSM cellular network (2G) coming along also with the first data services (SMS, GPRS, WAP). Then 3G brought about new radio technologies, better security and full data services, and 4G made a further step towards the confluence within the Internet, which we believe will be a major unifying feature of the emerging 5G, as we will discuss later on.

In parallel, Local/Metropolitan Area Network technologies started from wired, proprietary, low capacity systems and later on extended their realm in the transport network backbones. Meanwhile, the end of the 90s gave the start to an impressive deployment of wireless LANs, which, starting from little more than a low-rate cable replacement, have now almost topped the 10 Gb/s speed (e.g., the incoming IEEE 802.11ax technology), have become the most common Internet access technology in the home/office/campus, and are being smoothly integrated in the 5G network.

Meanwhile, also the networking research trends have evolved along different dimensions and key aspects (Fig. 1 right-hand side). A first trend regards the diffusion of the networks both in space and in type, with specific infrastructures expanding both the reach and the functionality of networks (ad-hoc, sensor, mesh, vehicular, satellite, underwater, body, things, nanothings, etc.). Similarly, a second obvious trend regards the improvement of physical systems, increasing the performance of copper, radio, optical, and now quantum communications.

The third trend highlighted in Fig. 1 is probably more subtle, and cannot be dismissed by simply saying that networking research, in the very early days mostly focused on lower layers (MAC protocols, routing), has shifted towards higher layers. In fact, such trend also regards the functionality implemented in the network according to the ISO/OSI stack: increasingly higher layer functions are executed also within the network, rather than in end-systems only. This is a general trend over the almost 50 years of research in packet networks (remember that the first packet was transmitted over the ARPANET in October 1969): we can identify a drift of the interest of researchers towards progressively higher layers (from levels 2 and 3 to layer 4, then to applications, overlays, and to problems that can be solved through networking). In application domains, research moved from contexts in which adequate technology was not available and had to be developed, to contexts where several technologies can solve the problem, and the best one must be chosen, adapted, and possibly customized.

A paradigmatic example of this change is automotive. When the PROMETHEUS Project was launched at the end of the '80s, on the occasion of the centennial of the first automobile by Daimler and Maybach, some of the use cases which are popular today were defined, such as platooning, cooperative maneuvering, and even autonomous driving. However, in those years, technology was not available, and research had to focus on technology development. More recently, research has been focusing on the applications and their requirements, and the issue has become the choice among the existing technologies for V2V communications, or V2I, or cellular.

2.1. The rise (and initial fall) of "intelligent" networking

This last example clearly shows how the ability to blend applications' needs into network customization opens up to a plethora of new services and opportunities. Technically, this translates in a more general quest for network nodes and devices whose behavior can be reprogrammed. Such quest is not nearly new, but dates back to at least the 90s.

Indeed, in the last 20 years, research on network programmability has undergone major hypes, intertwined by severe reality checks. For what concerns wired systems, as thoroughly outlined in [6], the ideas behind programmable (or even active) networking [7] pre-date of at least a dozen of years the advent of the Software-Defined Networking (SDN) era, and the today's focus on virtualization and "softwarization" of network functions. Some of the early active networking approaches, such as the "capsule" approach from [5] and its run-time reprogramming of network nodes via in-band distribution of mobile software code inside network packets, are even more visionary and forward looking than most of the current network programmability proposals. As analyzed in depth in [6], these early initiatives arguably failed not because of their vision (the Capsule model [Wet98] was perhaps extreme, but many other proposals at that time were revolving around a more controllable and manageable out-of-band router programmability model, conceptually closer to the current SDN model). Rather, they most likely did not came to life because they could not convincingly solve the dichotomy between (i) the idealistic goal of true flexibility and complete programmability which animated such pioneering initiatives and (ii) the pragmatic real world constrains of high performance, low cost, security, controllability, and compliance with commodity hardware and vendors' need for closed platforms.

Interestingly, even if programmability in the radio domain has evolved largely independently from that in the wired networking domain (at least until more recent convergence trends [8]), it has stuck as well into the above mentioned dichotomy. The seminal idea of dynamically (and autonomously) reconfiguring the radio behavior on the basis of the context and spectrum conditions, and its concrete translation into Software-Defined Radio platforms, was conceived in the 90s as well [Mit99]. However, it remained a niche area mostly restricted to dynamic spectrum management, opposed to the much higher and holistic initial expectation, and the gap between research platforms and practical deployment remained huge. As very clearly discussed in [9], "*research on vital questions has been extremely variable, with wonderful work (such as finding the right mix of programmable hardware to support high performance signal processing in radios) undermined by almost complete neglect (such as how to describe radio behavior independent of platform and how best to share spectrum)*" – in other words (and as we will discuss in Section 4), the availability of pragmatic, viable and secure platform-independent programming abstractions and network APIs could make a huge difference in terms of impact!

3. The situation today

The layman reader may wonder why Fig. 1 does not explicitly lists an "Internet" box below the evolution of networks column (and it is mentioned in the middle convergence box). The reason is obvious for any person with networking background: the Internet was in fact not a network technology itself (in contrast with LANs, WANs, or Cellular technologies or systems), but was focusing on the inter-networking among such underlay technologies, to provide end-to-end services.

But is this still true today? If, once upon a time, Internet was one among the services and arguably perhaps a marginal one if compared to the circuit-switched voice service, today the traditional differences between Telecom/communication and Internet/computer science communities is blurring (or has blurred), together with the integration of telephone/cellular and Internet/data networks. This process is shown in Fig. 2, starting with TCP/IP being an overlay of network technologies (the IP-over-anything frenzy), then with TCP/IP natively deployed in each technology, then today with TCP/IP having integrated all pre-existent network infrastructures and starting to include in the network also transport and application functionality.

In the meantime 5G (the 5th generation of the cellular networks) is threatening this model, being more ambitious than previous cellular generations and aspiring to play a bigger role. In fact 5G is being designed by including also the wired/core section of the network, as well as LANs (as a matter of fact, important characteristics of 5G would be meaningless if confined to the cellular section proper, e.g., the slice concept, see below), architecturally integrates cloud/fog and is natively a software network providing differentiated service support. Thus the current Internet and 5G are almost on a par with each other and converging to an integrated fully inter-operable network absorbing also (at least in part) applications.

3.1. The 5G "integrated" view

To better understand this last point, it is useful to look to the work in progress currently labeled as "5G", but which in practice has already crossed most of the traditional barriers between inter-networking and network technologies, incorporating important parts of the former (i.e., of the Internet!) into the latter [18–20].

Along with its explicit threefold challenge (*provide higher/denser data rates, support massive machine-type communication, and enable ultra-reliable and low latency communication* [17]) 5G envisages an orchestrated end-to-end architecture, not limited to the cellular section, and a convergence between fixed and mobile networking services with the associated evolution of core and transport networks. Importantly, 5G will fully exploit cloud computing and storage solutions, a trend that is wide spreading and transforming the main communication model from device-to-device to device-to-cloud-to-device, in which the smartphone is becoming more and more a way to access artificial intelligence services.

In addition to the expected *performance and energy consumption improvements in the radio interface, the integration of fronthaul and backhaul into a common transport network, and the significant step forwards in terms of security and reliability*, a further fundamental characteristic and main innovation of 5G is the so-called *Network "Softwarization"*. The underlying motivation is quite obvious and intuitive: replace specialized hardware components with software components running on general-purpose hardware platforms, thus harnessing the advantages of software in terms of cost reduction, automated update and lifecycle management, flexible workload management and dynamic deployment of functionalities, agility and fast service provisioning, etc.

Very importantly, a softwarized network can be virtually divided in so-called slices. "The network slice is a composition of adequately configured network functions, network applications, and the underlying cloud infrastructure (physical, virtual or even emulated resources, RAN resources etc.), that are bundled together to meet the requirements of a specific use case, e.g., bandwidth, latency, processing, and resiliency, coupled with a business purpose" [18]. Thus, the slicing concept is equivalent to being able to create end-to-end virtual networks at the service of a class of applications helping in providing the capacity to support the classes of service defined above.

Taking stocks, 5G is not just an evolution of 4G in terms of performance but creates a breaking point with respect to previous generations, and with an end-to-end architecture which blurs and crosses many boundaries with respect to our historical definition of Internet and inter-networking. Moreover, the focus on simultaneously supporting (possibly via slicing) widely different services and "vertical" applications will make of 5G a much larger ecosystem, including more stakeholders than in the past, with more complex relationships, more heterogeneity and more dynamicity. Applications sectors will be more and more actively involved in the creation and provision of services to users, taking full part in the 5G value chain. Last but not least, and of

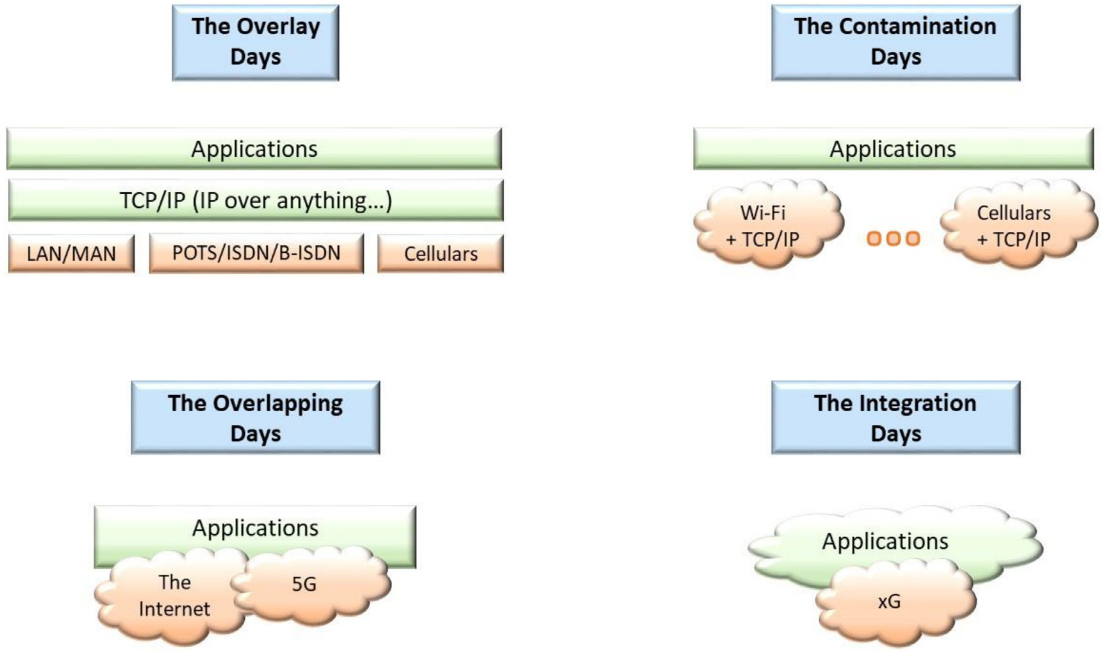

Fig. 2. The evolution of the Internet architecture.

major interest for the purpose of this paper, cloud integration and softwarization will provide a viable technological infrastructure and an in-network "knowledge plane" - quoting Clark et al.'s vision [10] - which, if today is "just" used for cost saving and flexibility, may turn (as discussed in the next section) into an unprecedented and pragmatic "arm" for realizing the ultimate promise of a truly cognitive network.

4. Tomorrow: Living and Fluid networks?

If understanding the past, and rationalizing the present, are already two difficult tasks, predicting what can happen in the future is extremely risky, and very error-prone. However, even if we lack a crystal sphere, we posit that in the next years we will see the emergence of what we refer to as ***Living and Fluid Networks***, namely network architectures holding the unprecedented ability to (autonomously) change so as to best adapt to context. In ***Living and Fluid networks***, algorithms and protocols will be capable of understanding what they are used for, and will tailor their algorithms and parameters to best suit the requirements of the different applications, appearing in different ways to different packet flows, behaving differently for each one of them, and providing the desired performance to each.

Unlike the early cognitive networking insights recalled in Section 2, we believe that the time for such networks has now come, due to the reached maturity of their two fundamental and complementary aspects:

i) the unprecedented modularization and "fluidification" of computing and networking building blocks brought about by modern programmable networking trends discussed below (i.e., the "fluid" aspect)*, and*
ii) the ability to take autonomous (or semi-automated) cognitive orientation strategies and reconfiguration decisions, as provided by the extremely effective and increasingly pervasive modern artificial intelligence approaches (i.e., the "living" aspect), and the intertwining of data and functions inside the network.

4.1. Fluid networks: functions and protocols' deployment on the fly

When discussing about network adaptation, the layman's understanding is that of very flexible frameworks and systems whose relevant parameters can be dynamically configured. Actually, we believe that time is already mature for more than "just" parameters' tuning, and that the next generation of programmable networking technologies will permit to get rid of the "*a new protocol per problem*" era, i.e., maintain the bold promise included in the title of a 2011 Open Networking Summit's keynote by Scott Shenker (a leading scientist in the Software Defined Networking arena, and co-inventor of the renowned OpenFlow abstraction): "the Future of Networking, and the Past of Protocols".

Rather than relying on a pre-established, hard-coded, protocol operation, an end-device could enter a network (think for instance about a user accessing a foreign cellular system), download the protocol(s) employed in that specific context [11], and readily turn the (initially general purpose) device into a terminal behaving as specifically desired by the network operator itself [9], irrespective of any a-priori standardization. Similarly, bare-metal switches and network nodes with a pre-configured forwarding behavior could be replaced by software nodes: extending the network so as to support a brand new protocol, or even permitting the operator to customize (or even craft from scratch) the network operation most appropriate in the considered deployment, and best fitting the contingent traffic and service needs, would be as easy and fast as a software download and upgrade.

The reader might say at this point: *what's the problem? Aren't most protocols just "pieces of software"? Can't they be simply uploaded over network nodes*? In principle yes, and – as a matter of fact – some of these ideas were not only imagined but even experimented more than 20 years ago in the active networking realm. But in practice, as the lack of any meaningful real world deployment of active networking has taught us, there are a few make-or-break viability issues.

A basic one is obviously security: the ability to deploy code inside the network nodes clearly opens a number of threats. However, it is a matter of fact that SW code is nowadays already largely moved and dynamically deployed on end-systems, and many baseline approaches (such as code integrity verification via digital signatures, access control, etc.) can be inherited from such realm. We remind the reader that even if security is frequently mentioned as the killing reason for Active networks, there were "secure" active networking proposals also at those early times, see, e.g. [12].

Rather, a more subtle issue, which our community succeeded to address only very recently, was the need to complement SW-based (slow) virtualized network functions with HW-based **platform-independent programming abstractions** (such as OpenFlow [13], OpenState [14], and P4 [15]), capable to guarantee (i) a non-trivial level of HW programmability, as needed to implement a potentially complex and stateful network task, meanwhile (ii) **guaranteeing line-rate performance** (as opposed to current SW-based network functions), and (iii) **consistency with the vendors' need for closed platforms**. Indeed, without such a fundamental requirement, the obvious solution would consist in permitting the programmer to access the internal details of a fully open platform so as to allow low-level custom programming of multiple network functionalities along with their control interactions. However, convincing network equipment vendors to open their platforms so as to permit full programmability is challenging, to say the least. Network device manufacturers have spent time and money to develop their products internally, and are hardly willing to make such investment available to *everybody*, hence including their own competitors. Moreover, when dealing with packet level processing operations, subject to strict timing issues and real-time requirements, vendors may extensively leverage hardware acceleration, from commodity TCAMs or SoCs, to dedicated ASIC implementation of specific functions, thus ruling away the possibility to program the device without knowing the underlying platform's details. Finally, full openness may even be counter-productive. Different platforms may have large internal implementation differences such that code developed for a device may need a complete rewriting to be ported on another brand, and this *multiplication* of code versions may turn into a deployment hurdle rather than an enabler. This can be observed with today's ossification of network control and management protocols and systems.

Taking stocks, there is certainly plenty of work still to do, especially in terms of providing concrete and usable security models, identifying the elementary reusable modules necessary to build complex protocols or network functions, and accordingly generalize currently proposed platform-agnostic network programmability approaches. But we believe that the time for fully programmable, fluid networks, is right across the corner, a time where "any" whatsoever network function or protocol stack will be deployed on the fly, irrespective of its performance requirements, complexity, and scale.

4.2. Living networks: harnessing AI and data analytics for self-adaptation

The coming of age of artificial intelligence (AI) that we are witnessing in these years, coupled with data collection and analytics, will have a profound impact in networking, opening many possibilities to autonomous behaviors in network evolution and adaptation to context, hence to what we call "living networks".

Living networks will exhibit "human-like" (or at least robotic-like) behaviors, being based on a fluid programmable infrastructure, augmented with artificial intelligence algorithms that, by exploiting the knowledge that they can acquire (observing the network usage patterns in time and space, the network performance for the different applications, the end user requirements, etc.), are capable of always reconfiguring the network and the available resources in such a way to deliver the most desirable behavior, measured in terms of a multidimensional set of quality and performance indicators.

Living networks will be capable of learning from the use they experience and from the performance they provide, reacting to predictable patterns, anticipating resource requests, forecasting errors and malfunctions, and reconfiguring available resource to best serve user requests.

The end users of fluid networks will behave as resource prosumers (producers/consumers), thanks to direct communication capabilities and crowdsourcing approaches for the adaptive provisioning of capacity through privately owned devices and/or small cells or access points, capable of implementing an adaptive crowdsourced network densification where needed and when needed, under the control of the network AI algorithms.

Some preliminary efforts in this direction are already visible, such as the WNOS by Melodia, [16] that provides an early stage autonomic control of a distributed wireless network, capable of optimizing the network operations across layers, based on the current network conditions. Much more is likely to come, and to have a drastic impact on the networks that we know, probably making the protocols that we use today look very old-fashioned.

5. Conclusions

In this opinion paper we tried to speculate on future evolutions in networking, building on the observation of what is happening today in the two areas of most vibrant networking research, corresponding to the two main network infrastructures of our times: the Internet and the cellular network. Considering the most visible research directions supported by standardization fora, we gather that a likely way forward in networking will consist in the emergence of networks which are capable of evolving and managing themselves. The autonomous evolution of these networks will allow them to mimic the behavior of *living* beings, and to exploit a stratum of *fluidified* networking and computing resources, where the term fluidified indicates that such resources are largely interchangeable, and dynamically organized and managed by more and more intelligent and autonomous algorithms. This new breed of Living and Fluid network architectures will exhibit an unprecedented ability to adapt and change, so as to best match the context and the user needs. In these Living and Fluid networks, all algorithms and procedures will show an extreme level of adaptability and reconfigurability; for example, protocols will be capable of understanding what they are used for, and to tailor their algorithms and parameters to best suit the requirements of the different applications, appearing in different ways to different packet flows, behaving differently for each one of them, and providing the desired performance to each.

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