Towards Smart Community Networks

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***Abstract*—The advent of IEEE 802.11 in the late 1990s spurred the development of new network paradigms. In particular, new technology enthusiasts saw the potential of Wi-Fi to bring broadband Internet connections to under-provisioned areas, giving rise to networks deployed and maintained by their users. This paradigm led to non-profit decentralized structures that grow by the unplanned addition of heterogeneous network devices: community networks (CNs). There have been hundreds of CN deployments worldwide; some have disappeared, while others have blossomed into complex networks with thousands of nodes. The networking research community has been aware of CNs, and many works studied CNs in their various aspects: design (routing, scalability, security), deployment, measurements, services, etc.**

We argue that emerging technologies will give a new impetus to CNs by transforming them into smart CNs. This paper aims to lay out the technical features of future CNs and encourage the research community to tackle the stimulating research challenges they raise.

***Index Terms*—Community networks, wireless mesh networks, smart communities.**

I. INTRODUCTION AND SOA

The current pandemic showed us that a working Internet connection is not *just* an enabler of other human rights, as we already knew, but it is a necessity for many people to study, work and access basic services. However, 2.9 billion people, almost 40% of the world population did not have access to the Internet in 2021[1], a rate that grows to 61% in rural areas, worldwide. One key reason for this situation is that telecommunication companies have a business model that works best in densely inhabited areas, have large capital expenditures to deploy the infrastructure, and rely on the high number of potential customers to return on the investment. It is an *all-or-nothing* model that fails in regions where the population density is very low, houses are clustered in groups several km apart, and the cost of the *middle-mile* connecting them is very high.

One of the successful instruments that we have to reduce the digital divide is a Community Network (CN). CNs were born as wireless mesh networks to share a cable connection with houses that were not directly reachable by cable. Mesh networks don't require significant initial investment; they are bootstrapped with as little as one link and grow unplanned. Being CNs non-profit networks deployed by their users, they have typically been set up using low-cost off-the-shelf outdoor Wi-Fi routers using the unlicensed Industrial, Scientific, and Medical (ISM) frequency bands. As Wi-Fi technology has been a critical driver for CN, the development of the two is closely linked[2]. We identify two generations of CNs, mainly distinguished by the types of deployment enabled by the Wi-Fi technologies, ranging from the first simple infrastructures [1] to more complex architectures [2].

However, CNs are not wireless-only; some CNs evolved into a unique infrastructure that mixes wireless and wired connectivity, e.g., adding optical fiber links. Moreover, in addition to the technical expertise required to bootstrap a CN, organizational, economic, legal, maintenance, and other aspects may be necessary for long-term sustainability [3]. In some cases, ignoring the non-technical aspects has led to the failure of CNs [3].

This paper analyzes the state of CNs from a technological and research point of view, with mainly three contributions: first, we summarize the path of CNs in the last two decades, focusing on the design of two generations of wireless CNs that were analyzed in the literature, with their pros and cons; Second, we foresee the emergence of a third generation of CNs (3G-CN) which, in addition to the evolution of Wi-Fi, will incorporate recent advances in blockchain and AI, and we discuss the directions in which these technologies can be applied. Third, we argue that CNs can continue to be a key instrument to overcome the digital divide if they evolve, providing added value to their users beyond connectivity. We outline the challenging research items that need to be addressed to make CNs evolve into smart community networks based on past experiences and growing interest in this theme. Our final goal is to show that not only do CNs have a positive social impact, but they also provide the opportunity to carry on high-level applied research in the networking field. As a tangible example, we simulate a 3G-CN and study its penetration in regions that are now under-served. We use an innovative approach mixing open data and GPU-based ray-tracing to estimate the fraction of households that could be reached using 3G-CN with state-of-the-art technology. This

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[1] See ITU Facts and Figures 2021 https://www.itu.int/itu-d/reports/statistics/facts-figures-2021/

[2] CNs even contributed to its advancement, see for instance the notable technical work carried on during the so-called Battle of the Mesh event (https://battlemesh.org/) in which practitioners develop and improve their network software and protocols.

[3] For a worldwide overview of the state of CNs, please see the APC Giswatch 2018: https://www.apc.org/en/pubs/global-information-society-watch-2018-community-networks

has a double goal of showing the feasibility of a CN and of introducing new methodologies for high-impact research.

The rest of the paper is organized as follows: in Sect. II we review the technological evolution of CNs up to recent times; in Sect. III we introduce a new generation of CNs based on emerging technologies and we evaluate its feasibility; in Sect. IV we outline some of the applications that can provide an added value to the communities, beyond connectivity; in Sect. V we outline some of the open research challenges that are interesting for the networking research area. Finally, we add our conclusions.

II. FROM ROOFNETS TO LARGE SCALE CNS

With the diffusion of IEEE 802.11, the concept of mesh networks was introduced in ICT research. While there is no specific definition, a wireless mesh network is generally described as an infrastructure for which:

- The nodes are stationary (as opposed to a mobile ad-hoc network);
- Nodes are both generators/receivers of traffic and routers of other nodes' traffic;
- There is no planning, and the network is self-healing: nodes can be added or removed, and the protocols must make new nodes reachable and/or *route around* failures without manual reconfiguration.

The first generation of CNs (1G-CN) used commercial off-the-shelf (COTS) 802.11b/g access points mounted on house roofs or terraces, as in the MIT Roofnet [1].

The advantage of this design was an extremely simple set-up, with only one device to be mounted and configured, but the performance was extremely low. Omnidirectional antennas can cover short distances (up to hundreds of meters), and the network capacity scales sub-linearly with the number of nodes, as the interference is hard to mitigate when the spatial density increases. As soon as 802.11 became popular, the unlicensed bands started to be crowded, and the idea of creating general-purpose, large-scale mesh networks with this design faded.

A. Motivations and Design of a Modern CN

To be usable in under-served areas with low house density, the wireless links of a CN need to span across several km, which encouraged a second generation of community networks (2G-CN). The single COTS device on the roof is replaced by a set of outdoor ISP-grade point-to-multipoint devices using Power over Ethernet (PoE) and mounted on one (or more than one) pole on the house's roof (as depicted in Fig. 1). The devices create links spanning several km, powered by 802.11ac with up to gigabit performance (see Tab. I). They need to be connected to a router that will take care of the routing of packets, plus a home access point to provide connectivity to the terminals inside the house. 2G-CNs enable networks made of hundreds [4] or even thousands of nodes [2] covering very large regions.

TABLE I: Link characteristics for different generations of CNs.

gen.	standard 802.11	antenna type	band GHz	throughput Mbps
1	b,g	omni.	2.4	< 20
2	n,ac	sector, ptp	2.4, 5	20$\sim$300
3	ac,ad,ax	ptp, beamf.	5, 60	100 $\sim$1000

Such a CN is a techno-social artifact: an unplanned distributed network that adapts to the addition of new nodes, mirrored in a distributed community that grows spontaneously one person after the other. Since the network is non-hierarchical, there are (ideally) no nodes that are more important than others. Thus, the owners of the nodes organize in agile peer-to-peer communities with very lightweight coordination. CNs are generally treated as a not-for-profit initiative held in commons, often with no legal entity, which makes them easy to bootstrap, the exact opposite of the *all-or-nothing* model we mentioned. This design sparked a body of interdisciplinary research in ICT [5], social systems analysis [6], network economy [7], and many more.

However, 2G-CNs design has three big drawbacks. The first is the complexity of the architecture, which now requires configuring at least three devices with a non-trivial network and physical set-up, as shown in Fig. 1. The second is the increased cost, which can reach several hundred euros per node (with a large variability). The third and most critical is the loss of self-healing capacity, as directive antennas need to be re-pointed or added when the topology is modified. With this network design, every time the conditions change (a new link is created or some link fails), a trained person needs to climb onto a roof (in someone else's house), physically modify some existing nodes, and reconfigure the devices. Consequently, 2G-CNs strongly rely on the initiative of some technically skilled members of the community to be maintained. Their technical structure tends to centralize because a few, better-equipped nodes are easier to maintain, and the social structure, while still being perceived by the community as a peer-to-peer distributed one, inevitably degenerates into a highly centralized and fragile one depending on a few skilled individuals. When the network grows too much to be maintained by a small voluntary team, its performance and reliability degrade, and the community fades. This is a structural limitation of current CNs that has been measured analytically in one case [6] and led to the decline of some initiatives[4].

Future CNs will have to improve in two directions to make the community less dependent on a few individuals: i) improve the manageability; ii) provide added value beyond connectivity to enlarge the user base. We foresee two possible ways to overcome this limitation, which introduces very interesting research challenges. The first is a 3G-CN design based on new technologies that can make the network easier to maintain. In Sect. III, we explain the technological building blocks and provide data to assess its feasibility. The second requires better

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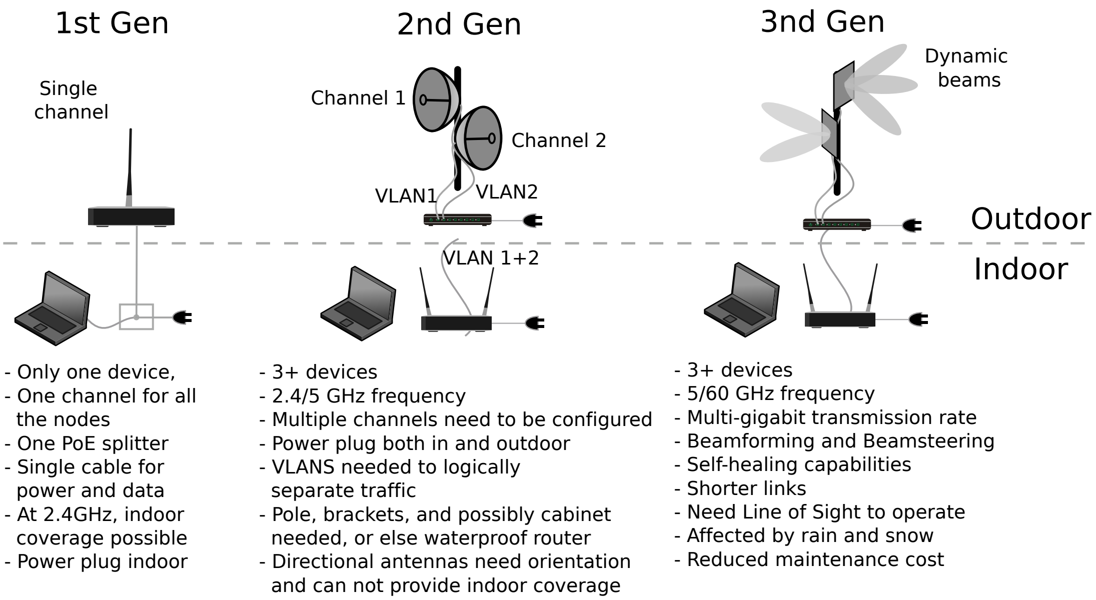
[4] See the "Report on the Governance Instruments and their Application to CNs" of the netCommons Project: https://netcommons.eu/?q=content/deliverables-page.



- Only one device,
- One channel for all the nodes
- One PoE splitter
- Single cable for power and data
- At 2.4GHz, indoor coverage possible
- Power plug indoor

- 3+ devices
- 2.4/5 GHz frequency
- Multiple channels need to be configured
- Power plug both in and outdoor
- VLANS needed to logically separate traffic
- Pole, brackets, and possibly cabinet needed, or else waterproof router
- Directional antennas need orientation and can not provide indoor coverage

- 3+ devices
- 5/60 GHz frequency
- Multi-gigabit transmission rate
- Beamforming and Beamsteering
- Self-healing capabilities
- Shorter links
- Need Line of Sight to operate
- Affected by rain and snow
- Reduced maintenance cost

Fig. 1: Comparison between CN generations.

integration with services that can make CNs attractive beyond Internet connectivity, provide added value to the participants, and thus create new economic incentives to make CNs self-sustainable (we cover it in Sect. IV and V).

III. 3RD GENERATION COMMUNITY NETWORKS

The advent of 5G encouraged research on communications at high frequencies such as mmWave (beyond 24 GHz) and Terahertz (beyond 1 THz) communications, where there are large unused portions of the spectrum that can be used to provide high throughput links. Moreover, high frequencies need smaller antennas, so we can have Massive Multiple Input Multiple Output (M-MIMO) antenna arrays made of tens of elements to enable beamforming. A MIMO device covering a sector of 120° can create a narrow beam aimed in the direction of the receiver, achieving a transmission (and reception) gain close to the one achievable with a directional antenna and reducing the overall interference. The beam is steerable in a dynamic way, so the advantage of having a point-to-point link does not come with the disadvantage of manual aiming, as with directive antennas. However, at high frequencies, the propagation of signals is challenging. The communications happen primarily in line-of-sight as obstacle penetration is impossible, and fading due to rain, foliage, or even atmosphere is way more impacting than at the unlicensed spectrum used by 802.11n/ac.

While these techniques were primarily intended to improve radio access in mobile 5G networks, mesh networks at high frequencies are the next step. For instance, 5G supports backhauling via mesh networks (referred to as Integrated Access and Backhaul, which is receiving considerable attention from the communications research area). In contrast, in the unlicensed spectrum (60GHz), commercial mesh devices are already available, like the products that support the Facebook/Meta Terragraph mesh network, providing gigabit performance.[5]

Given these recent advances, we can imagine a forthcoming 3G-CN design using higher frequencies than the classical 2.4/5 GHz spectrum, from 24 GHz up, and based on two building blocks: i) MIMO devices that create links in line-of-sight with steerable beams of length lower than one km to create dense local meshes; ii) a minimal number of long links spanning several km, using directional antennas to connect the otherwise disconnected meshes. 3G-CN mesh nodes look similar to the second one. Still, the large majority of the antennas do not need to be pointed, and once mounted and configured, they don't need human intervention to create new links, which makes their management way easier than 2G-CN mesh nodes and recovers the self-healing capacity. In contrast, link length is reduced substantially, and line-of-sight is required. Thus, we must answer the question: is it feasible to achieve widespread population coverage in rural areas with a 3G-CN?

A. *Simulating The Coverage of 3G-CNs in Rural Areas*

To evaluate the possible coverage of 3G-CNs, we adopt a data-based methodology we introduced in a recent paper [8] that can be fully re-used in this, or other contexts. We start from a 3D surface obtained by open data from public administration that represents a certain municipality, we identify buildings using open maps, and we use open demographic data to obtain the number of households for every *census section*, which is a subset of the area of the municipality. Using the 3D shape, we estimate the volume of the buildings, exclude the ones smaller than a certain threshold, and assign to each building a number of households proportional to the

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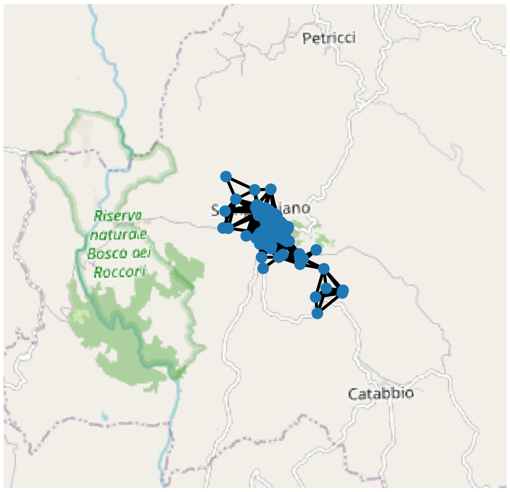
[5] See https://terragraph.com/.

volume, up to the number of households in the area. Of the total number N of buildings, we randomly select a fraction ρ of buildings, with a probability distribution that follows the number of households per building. We ideally place an antenna on top of the building roofs, assuming a 2 m tall pole, and we then follow a 2-step heuristic: in step 1, we use ray-tracing to compute the line-of-sight between every couple of buildings in the area, setting a maximum link length of 600 m. We extrapolated this value from the specifications of the Terragraph hardware as published by Facebook/Meta[6], which reports links up to 450 m (600 m) with a throughput of roughly 1 Gb/s (200 Mb/s). Step 1 creates several disconnected clusters, which we try to connect with longer links. In step 2, for each couple of clusters larger than one node, we search for a feasible line-of-sight link of length up to 4 km. This distance is instead extrapolated by the data-sheet of the point-to-point Ubiquiti airFiber 60XG[7], certified as compatible with Terragraph. We consider the resulting graph, and we count the nodes M in the largest connected component of the network graph. We evaluate a coverage metric λ given by M divided by the number of potential nodes in the network ($\lambda = \frac{M}{N\rho}$) that provides an estimation of the coverage of wireless CNs in the selected areas. If $\lambda = 1$, then all the nodes we randomly chose are part of the connected component of the mesh network, which means that a network connecting all the nodes can be successfully realized. If $\lambda < 1$, then not all nodes can be reached by the mesh network, and it is essential to evaluate how close λ is to 1.

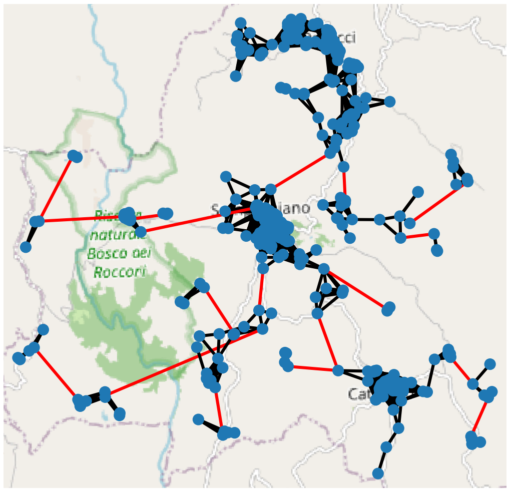
We use data from 10 rural areas in Italy that we selected among those considered digitally divided (the fastest wired technology that reaches *some* houses in the area is ADSL with legacy copper cables). Their size and the number of houses is reported in Tab. II. Given the large number of links for which we need to test line-of-sight (up to the order of 10^6), we use an NVIDIA GPU to parallelize the task.

For each value of ρ, and each area, we repeat 30 Monte Carlo simulations with a different choice of the buildings, and we report λ Vs ρ in Fig. 3.

Every point in Fig. 3 reports the average λ over 300 runs (10 areas times 30 runs) and the 95% confidence interval. The blue line is the value of λ when only step 1 is applied. Even without long links, roughly 50% of the houses can be connected. The red line is obtained with steps 1 and 2. It grows from 66% to 85% and shows that this technology can reach a very large proportion of the population. Note that λ grows with ρ, so some houses are key to connecting otherwise disconnected areas. With a random choice of the buildings, the probability of choosing these key houses increases with ρ (and thus λ increases). Still, with minimal network engineering, we believe λ can be increased even for lower values of ρ: In a real network, the community may set up nodes in strategic positions, or they may decide to use higher poles in the nodes that can not be reached. However, these simulations confirm that the current technology can enable 3G-CNs with a widespread population coverage in rural areas. In Fig. 2 two instances of a 3G-CN in Semproniano are shown, highlighting how a small number of longer links can dramatically improve coverage.



(a) short links only



(b) long+short links

Fig. 2: Two instances of the same network in Semproniano that attempt to connect all the buildings ($\rho = 1$), long links are colored in red.

Tab. II provides more details on the areas and on the results for the case $\rho = 1$ and shows that the density of the potential links (those that can be realized in line-of-sight) is extremely high. The average degree ranges from 13 to 252, which provides an extremely high diversity of paths between nodes and thus, resilience to failures. The number of links that can provide gigabit performance is the majority of the potential ones (except in one case), and, most of all, the number of long links that require manual reconfiguration upon failure is extremely low (less than 2 every 100 nodes). We can thus say that 3G-CNs would be much easier to maintain than 2G-CNs,

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[6] See the Terragraph Mesh Paper, Throughput Vs Range image, page 11: https://terragraph.com/docs/whitepapers. We use the 99.6 availability curve.

[7] The device is a point-to-point device capable of up to 6Gb/s at 60GHz, see https://dl.ui.com/ds/af60-xg_ds.pdf.

TABLE II: Summary of data when trying to connect all the buildings in the area ($\rho = 1$, N potential nodes).

Village	Area size (km^2)	Number of nodes (N)	Number of links (potential)	Number of links < 450m	Number of links > 600m
Borgo a Mozzano	72.2	2174.5	99398.4	59239.1 (60%)	3.5
Castel del Piano	67.8	1337.8	168956.3	96733.3 (57%)	0.6
Magliano in Toscana	250.7	1270.6	30299.3	12861.4 (42%)	23.2
Porcari	17.9	1066.4	59083.3	30518.5 (52%)	0.7
Roccalbegna	124.9	482.1	17128.7	13027.7 (76%)	0.5
Sambuca Pistoiese	766.9	1449	9577.4	6413.1 (67%)	6.5
Santa Fiora	63.5	1383.0	91653.3	48452.3 (53%)	4.0
Semproniano	81.7	711.4	24483.3	14966.1 (61%)	6.5
Stazzema	82.1	347.3	2367.5	2056.3 (87%)	3.8
Villa Basilica	36.6	574.4	13962.9	11291.8 (81%)	2.1

and finally more reliable in case of failures.

IV. FROM CNS TO SMART CNS

Smart and sustainable cities (or rural communities), as ITU-T defines[8], need interconnected information to understand and control their operations and optimize their limited resources. Information and Communication technologies can improve the quality of life, the efficiency of urban operations and services, and competitiveness while ensuring the needs of present and future generations concerning economic, social, environmental as well as cultural aspects. This is achieved by comprehensive environmental sensing: data on public infrastructures such as energy and water consumption, pollution, weather conditions, security, and safety, combined with data processing to automate well-informed, proactive, and efficient decisions with transparency and accountability, making a community smart. The nodes of CNs are strategically placed close to data sources and sinks (sensors and actuators on roofs) together with computing nodes with storage capacity (below the roof). This split physical design depicted in Fig. 1 is a peculiarity of CNs that help environmental monitoring practices. However, to support smart applications, CNs need to provide a faster, more reliable, and more easily manageable network, minimizing the dependency on manual interventions that increase downtime and lower reliability. To make a parallel, we can see 3G-CN as the innovation brought to mobile networks by 5G. They both improve performance and reliability and enable future added-value applications that are interdependent, co-located, and vertically integrated. Smart applications encourage participation and economic investment, fundamental to making a not-for-profit CN infrastructure sustainable in the long term, especially today that even for traditional telecommunication companies providing bare connectivity is less and less a profitable/sustainable activity.

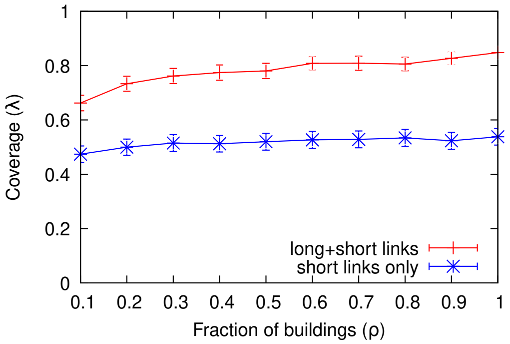

Fig. 3: Coverage of a CN in 10 rural areas of Italy.

In this section, we outline some of the promising applications that 3G-CNs can enable.

Smart applications for CNs: Organizations and people collaborate in CNs to achieve a shared goal. Thus, they are generally willing to collect and share their data in a privacy-respecting way to improve the operation and development of their neighborhood. In CNs, users already have network devices on their roofs and are excellent candidates for data collection and participation in smart city initiatives. Complementary data add detail and quality to environmental sensing, informing city-level and citizen-level decisions with more relevant data. That data pool can feed edge processing for informed and adaptive decisions and actuation. In fact, pooling brings scaling advantages to networking, data storage or computing, and co-location facilitates mutual support for smart decisions. Two examples are the use of data and applications for smart farming, which has been enabled in rural areas thanks to the presence of a CN [9], or initiatives that use the CN infrastructure to monitor air or noise pollution[9].

Edge Intelligence in CNs: Data become actionable when stored and processed. CNs offer local clouds with storage and processing of large volumes of locally relevant data, accessible at minimal cost and latency, away from the privacy and confidentiality risks of large cloud providers [10]. Tightly coupled with cloud storage is the opportunity of federated machine learning where data is processed near the generation point, and only locally trained models are transferred to a coordinating entity. This procedure has significant advantages over traditional centralized ones, such as data privacy and savings in energy and network bandwidth, and works for

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[8] See the ITU-T Recommendation ”Overview of key performance indicators in smart sustainable cities”, https://www.itu.int/rec/T-REC-L.1600-201606-I

[9] See, for instance, the SEA-HAZEMON project in CNs in Thailand and South Asia https://interlab.ait.ac.th/HAZEMON/.

both city and citizen-level control decisions and resources. Edge data and intelligence is a key ingredient for smart applications. Even the network infrastructure can benefit from that, allowing more automated self-managing networks. A big challenge is the development of a multi-layer software stack and network architecture, re-usable in different networks, similarly to the Open Radio Access Network (O-RAN) now under development for 5G[10].

Value Transactions on CNs: The sustainability of a CN depends on its economy, that is, how people share the cost of the infrastructure and its maintenance. Blockchains are suitable instruments to play this role in CNs as they provide accountability and transparency and are designed to work in communities of people with limited reciprocal trust. Permissioned blockchains, running on a set of small edge nodes, have been deployed and experimented in CNs as tools for network traffic metering and cost-sharing [11]. Once the Blockchain is in place, the flat and cooperative governance of CNs suites its usage as a form of alternative currency for reputation and value in exchange b data, work, and smart services.

CNs as Enablers of other Networks: Finally, we mention that 3G-CNs can become the backbone for other networks as a distributed internet exchange that adds even more value to the community. It is the case with CNs acting as Internet traffic exchanges, enabling mobile access or IoT applications that need a capillary distribution system.

V. CHALLENGES EMERGING FROM REAL CASES

CN solutions have open challenges due to their peculiar distributed, bottom-up infrastructure. As such, we need to keep in mind that centralized, top-down solutions for network management and economic sustainability that are widespread in other networks can not be easily applied. In this section, we mention some research challenges that are peculiar to CNs, coming from the observation of real cases.

Disintermediation:

If a smart CN becomes a key societal asset, the dependability on its operational status increases and thus the governance and management become more complex. The automation and verifiability of an increasing volume of information to deal with become a need to make sure the network operates smoothly. This is the case of network routing and traffic analysis to optimize and deal with traffic anomalies, attacks, or faults. Distributed ledger technologies (DLT) and blockchains bring technological solutions to implement networks that generally exchange verifiable data and value. They allow a trusted and verifiable accounting required to support the representation, management, and transfer of valuable information, such as funds. As a result, smart CNs can have truthful and verifiable information about service-level agreements, commitments, property, investment, payments, penalties, etc., recorded in a trusted manner and accounted for automatically by code in smart contracts that automatically execute, control or document relevant events and perform actions according to the terms of a contract. [11]. In addition, all these DLT applications can run on servers owned and managed by the smart CN, becoming an economical substrate for further smart CN applications, where network managers and end-users develop economic schemes for resource sharing and service provision and retribution. The scalability of such a system, the kind of blockchain, and how to map network resources to transactions in a verifiable way are still open research issues.

Economic:

Once analyzed the feasibility of 3G-CNs in terms of coverage, economic feasibility comes into play. With today's prices, a mmWave node can cost up to 2000 dollars, but as high-frequency technologies become widespread, we expect the price of devices to reach the price of 2G-nodes, about 200-300 dollars per node. Beyond radio devices, there are several other costs: upstream bandwidth, fixed network routers, and the computing and storage needed for smart applications. When a smart CN becomes a key asset for a whole community, its ecosystem must include individuals, IT companies, small telecom operators, cloud providers, non-IT companies or organizations from any related sector, and public organizations [12]. In the end, a smart community network will thrive if the infrastructure performs well and all providers and consumers have a positive balance in terms of investment and return value, so economic sustainability becomes fundamental.

However, the interplay between common goods and for-profit activities is highly complex to manage. Individuals need incentives for voluntary actions that naturally result in desired collective direction. Commercial activities use profit-oriented economic models to compensate for risk-taking, and the two models may conflict. One viable approach is to consider the network as a shared infrastructure owned by the community, that develops in a cost-oriented, not-for-profit model, equivalent to the model of Internet Exchange Points [7] and then allows commercial initiatives on the network for services [13]. Again, machine learning and blockchain could be the bridge between the two worlds, as models based on data processing combined with incentive schemes approved by the community can be implemented as smart contracts that, in exchange for actions, result in the automated generation of community currency transfers that can be spent to buy services offered in the network [11].

Technological:

Different technologies offer different sweet spots to satisfy network needs. Therefore, there is a need for a combination of technological solutions, including software tools to manage the integration of traffic management (e.g. routing), data collection and processing, and smart applications on top.

This is particularly true for CNs that often operate in market failure situations, in which the traditional *one-size-*

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[10] 5G is not a monolithic network as previous generations, and its interfaces are open ones, see: https://www.o-ran.org/

fits-all connectivity model is not applicable[11]. 3G-CNs must diversify, combining diverse connectivity technologies with multiple devices and service providers to offer the most cost-effective technology for each location, node, and person. That implies combining wireless, cellular, and wired connectivity [12] while managing location sharing, and more automated interconnection with higher amounts of traffic and economic compensation, for more resilient critical networks and smart applications. In some cases, these technologies are operated by different entities or third parties (including public and private for-profit companies) [13] as local internets. Managing such a heterogeneous network is an open challenge, and the smart aspects bring an additional challenge related to data management, data integration, smart data processing, and data protection. Vendor silos with limited interoperability and lack of standards on 3G-CNs are limiting factors.

Finally, machine learning is a pervasive technology that is also now being successfully applied in the field of networking. Federated learning, a form of distributed ML, shows it is possible to efficiently utilize network resources, automating management for IoT users and the operating costs for cellular operators [14]. Its application to a distributed network has been tested for traffic classification or anomaly detection, but we need more evidence on its scalability and applicability in real cases [15].

Governance:

As mentioned, CNs tend to develop in an organic and decentralized manner, developing with little planning compared to most large operator networks. That is similar to how the Internet has developed by setting up local networks that expand and interconnect. CNs require agreements for inter-operation and standards, similar to the global Internet. Coordinating this evolution while keeping a network operational and avoiding single points of failure [6] is an open challenge.

VI. CONCLUSIONS

CNs appeared more than two decades ago as not-for-profit networks built by their users to bring the Internet to under-provisioned areas. We identified the 1G-CN of easy-to-configure wireless CNs with simple omnidirectional antennas and the 2G-CN with a mix of devices, including directional antennas that build point-to-point links. However, that configuration comes at the cost of a larger budget, reduced self-healing, and management complexity.

We believe that advances in wireless technology will lead to 3G-CNs that will alleviate these problems, and we show its feasibility. CNs must enable smart applications to collect and process large amounts of data and become smart CNs, building on new technologies, and more automated governance and management. The goal of this paper is to outline the related research challenges and encourage new results on this scientifically intriguing and socially impacting theme.

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[11] One promising large-scale connectivity option is given by low-orbit satellites. However, their global performance, cost-effectiveness, and manageability are still to be demonstrated. Satellite networks are not yet an alternative to CN's communications needs, even if their integration with CNs is already part of the research agenda. See the recent discussion inside IETF on Satellite-Integrated CNs, https://datatracker.ietf.org/meeting/114/session/gaia

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