Connected OFCity: Technology Innovations for a Smart City Project [Invited]

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***Abstract*—Around the world, municipalities have been making substantial investments into broadband access infrastructure to accelerate the build-out of an urban phenomenon that has become known as a smart or connected city. At the 2016 Optical Fiber Communications Conference, a team contest, the *Connected OFCity Challenge*, was held to discuss the technological innovations and to examine dependencies and intricacies of a connected city project. The participants, four teams of experts coming from a cross-section of the industry, presented and defended their visions of future applications and innovative architecture and technologies to realize the interconnection. This paper provides a synthesis of the four competitive proposals offered for the contest and their ensuing discussions.**

***Index Terms*—Access technology; Broadband communication; FTTx; Optical fiber network; Passive optical network; Smart cities; Software-defined networking; Wireless network.**

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I. Introduction

The idea of smart cities dates back several decades [1]. As an example in the United States, in 2005 the Clinton Foundation urged the information technology industry to find innovative solutions to tackle pressing challenges in urban areas. Rising to the call, Cisco launched the Connected Urban Development Program with $25 million funding over a five-year period. Today, governments and institutions around the world are investing heavily into smart cities related research and development to improve municipal services and stimulate economic growth.

In September 2015, the Obama Administration announced a smart cities initiative with $160 million investment in federal research and new technology collaborations [2]. Since 2011, the European Innovation Partnership on Smart Cities and Communities (EIP-SCC) has been a key initiative investigating innovative solutions for environmental, societal, and health issues affecting European cities. In Asia Pacific, numerous government-sponsored projects aim to encourage smart city technology development in transportation, environment, water management, and education. It is expected that the annual investment in smart city technologies in the APAC region will reach $11.3 billion by 2023 [3].

During the planning meeting for OFC 2016, members of the N4 subcommittee (Optical Access Networks for Fixed and Mobile Services) proposed a workshop to discuss a smart/connected city project from the perspective of optical access network technology. In keeping with the spirit of *connectedness*, an idea also came up to connect the speakers into multidisciplinary teams and hold the workshop in a competition format—the very first attempt at OFC. A judging panel consisting of an industry analyst, a standards body chair, a venture capitalist, and a representative of the U.S. government smart cities initiative provided different perspectives to the discussion.

A fictitious metropolis, called *OFCity*, was created as the backdrop for the case study. Formulation of the geographic and demographic details of OFCity, described in Section II, was based on a survey of several U.S. cities. The plot line is as follows: as part of the growth plan, the OFCity council invested $100 million plus $50 million private matching funds to improve the city's broadband infrastructure by 2020. To ensure the funds were wisely utilized, the city council hosted an open competition, the *Connected OFCity Challenge* [4], to choose the most innovative proposal for the project.

Four multidisciplinary teams participated: ALIVE, FIBRUS, Ofconn, and TERAPOLIS. Each consists of academia researchers, component and equipment vendors, and service providers. The OFC workshop on March 21, 2016, was formatted as an open town hall meeting, at which the teams presented and defended their proposals in three categories: 1) supported services and applications, 2) innovative architecture and technologies, and 3) a realistic business plan.

As a result of the town hall meeting, two teams received the distinctions: Team Ofconn won the Judges' Award and Team TERAPOLIS won the Audience Award.

This paper is a synthesis of the four approaches and discussions during the competition and is organized as follows. Section II provides the geographic and demographic data of OFCity as well as contest questions and requirements. In Section III, each of the four teams describes the essence of their innovative proposal in a stand-alone subsection. Section IV summarizes the findings.

II. Assumptions and Requirements

This section describes the important, albeit fictitious, geographic and demographic data of OFCity. These values were determined after surveying characteristics of several mid-size U.S. cities and were designed to encourage innovative solutions in addressing the contest questions and requirements in a representative case study.

A. Background Information About OFCity

OFCity is envisioned as a historic regional center with several small cities nearby. A historic map of Vilnius [5], the present-day capital of Lithuania, was chosen to give a visual image of OFCity, with the major infrastructure sites marked in Fig. 1. The city is about 400 km^2 in size with a population of 550,000 and 262,000 households, of which 60% are single-dwell and 40% are multi-dwell units. It has a typical post-industrial demographic makeup with a vibrant youthful population—highest percentage in the 20- to 40-year-old age group. There are 25,000 private-sector businesses in the city.

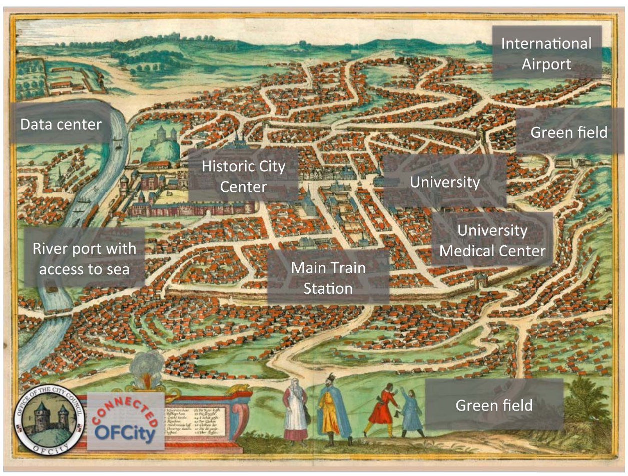

Fig. 1. Map of OFCity.

TABLE I
Existing Broadband Deployments

	Residential	Business
No broadband	20%	N/A
Passed, not served	40%	N/A
Coax	19%	15%
DSL	19%	60%
Point-to-point fiber	2% (FTT Building)	5%
Fixed wireless	N/A	20%

TABLE II
Budget Model for Extending Fiber Connections

Fiber Penetration	CapEx
75%	$75 million
88%	$112.5 million
95%	$150 million
100%	$180 million
Available cash: $150 million	

Currently, 60% of the residents are still without broadband connection, and 60% of businesses are connected via DSL (Table I). The purpose of choosing a low percentage of FTTx deployments is to encourage more emphasis on optical fiber technology-based proposals.

B. Requirements of the Challenge

To be considered a winning proposal, the teams were asked to explore innovations and present the rationale and benefits of their approaches in three focus areas:

1) Services and applications to improve citizens' lives and foster economy growth.
2) Technology innovations, network architecture considering both wireline and wireless aspects, and new infrastructure build-out if needed. The emphasis is on advanced technologies to extend fiber connections to over 75% for both businesses and households. Operational details are not considered.
3) Realistic business plan with efficient use of resources, risk management, and supporting sustainability and environmental protection. No digging is allowed within the 1 km × 2 km footprint of historic city center.

The budget model in Table II is used to estimate the capital expenditure (CapEx) required for extending fiber connections to businesses and households. Each team can choose the suitable budget for their particular design.

III. Team Proposals

In this section, the four teams discuss the rationale behind their solutions and how they address the three categories of questions: services and applications, architecture and technology, and business plan.

A. Team ALIVE

By M. Ruffini (lead), T. Forde, K. Bourg, E. Dai, and E. Harstead.

In approaching the OFCity challenge, Team ALIVE decided to tackle the project from the citizen's perspective, i.e., to develop the proposal from the bottom up, looking at the hypothetical needs of citizens in a truly connected city, rather than the conventional top-down approach with a network solution that would be *imposed* on the city regardless of the anticipated needs of end users.

The team name itself, standing for *the Augmented LIVing Experience*, emphasized the goal of delivering a service-oriented network.

We thus went on proposing a number of future services we believe would *augment* citizen lives, improving their quality of life. We tried to avoid the temptation to look for applications and services that would justify the network but only focus on what could bring novelty in the lifestyle of a city. We then derived the requirements and guidelines for the network architecture and an appropriate business model. This approach parallels the development process increasingly being adopted in the wireless domain.

Technical solutions in 5G cellular networks are driven by new user demands and new user sectors. For example, some service providers have started building dedicated mobile networks rather than running services over existing (general purpose) ones, which cannot ensure the required quality of service (QoS) for target applications.

1) Services and Applications: One of the most fundamental resources in a living environment, such as a city, is geographical space. It is possible to liken this resource to network hardware; thus its functionality and usage can be augmented through virtualization. Therefore, OFCity is for us a place where much of the space is open access, shared, and virtually allocated depending on citizens' needs. During the development of our solution, a recurring question was "Do corporations still need to exclusively own physical space?" The association between physical space, be it offices or factory floors, and a corporation is a concept inherited from the industrial revolution when buildings and spaces were outfitted with specialized machines to produce specific physical goods. Today, much of the worldwide business focuses on producing service-oriented virtual goods, often delivered in the form of software. Many traditional manufacturing-type enterprises are confined to limited zones of cities while new *virtual production* happens throughout urban areas.

Therefore, we proposed that part of the city space be shared and can be reserved by different organizations as a virtualized working environment for their employees. An extension of this idea applies to the education sector, where virtualization allows for the decoupling of the institution offering the service from physical locations. This concept could potentially be applied from childcare to university. In addition to space reservation, educational institutions can also share expertise (e.g., lecturers and laboratory assistants) to fill in temporary deficiency, augment their knowledge in a specific area, or cover new trending topics not properly addressed by permanent academic staff. This could be an evolution and maturation of the massive open online course (MOOC) concept, which has gained success in bringing modules taught by top-level academics to everyone with an Internet connection. The increasing demand for, and supply of, educational services will in turn stimulate more specialized teaching modules while giving students more control over their learning path.

Space virtualization is strongly related to smart transportation, where we envision an *Uber+* service enabling predictive and on-demand scheduling, allowing citizens to move between different locations throughout the day without wasting commuting time. For example, a portion of the public transport fleet allows for desk work space, meeting or video conferencing facilities. The boundaries that differentiate concepts such as smart office, smart home, and smart vehicle begin to blur as communication technology enables users to adapt spaces to their needs rather than the other way around.

While services anticipated for smart transportation were not specifically designed to justify a better network, for 5G, the target minimum guaranteed capacity per user is 500 Mb/s. Truly ubiquitous coverage, with a minimum 50 Mb/s capacity, is a must for the success of 5G for all verticals, including the automotive sector [6]. In addition, the requirement that physical space is used for different service scenarios implies a highly reconfigurable connectivity, in order to enable varying demands from best effort connection of tens of Mb/s to dedicated capacity of several tens of Gb/s.

2) Architecture and Technology: The architecture of choice to enable *full reconfigurability* is a power-split passive optical network (PON), with multiple technologies operating over the same infrastructure, as depicted in Fig. 2. The same infrastructure must serve both residential and business customers as well as future mobile connectivity in a seamless and interchangeable fashion, as the space virtualization concept will eliminate any distinction throughout the network.

We envision that most users will make use of 10 Gb/s symmetric PON (XGS-PON) [7]. XG-FAST [8] is another option to terminate the drop-in locations where installing the last fiber span is inconvenient or expensive.

Users demanding higher reconfigurability, for example to enable on-demand capacity of up to 10 Gb/s, will require the flexibility of NG-PON2 [9] and more expensive ONUs. Locations that require on-demand services of hundreds of Gb/s might employ a point-to-point wavelength link as an overlay over the physical PON fiber. This could be based on coherent transmission technology using DP-QPSK or higher-order QAM.

Upgrades will occur as technology becomes available; for example, the channel rate may become 25 Gb/s on both XGS-PON and NG-PON2, following the 25 Gb/s technology brought about by 100 Gb/s Ethernet work in IEEE.

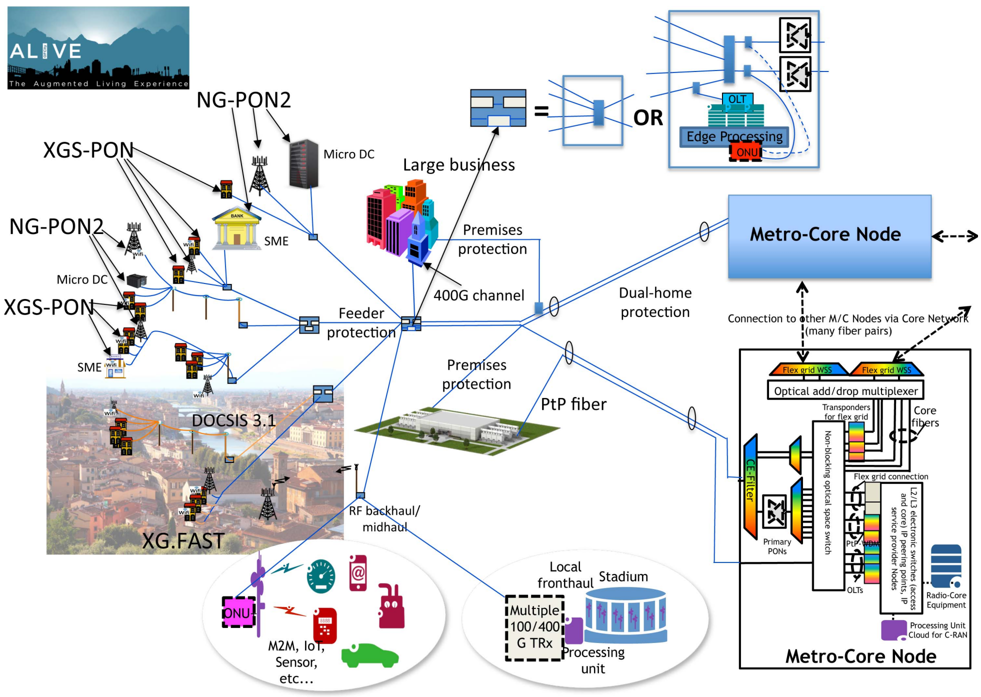

Fig. 2. Access-metro architecture envisioned by Team ALIVE.

Operators believe that capacity increase to residential users does not constitute a major challenge, as current PON standards can satisfy user demand for the foreseeable future [10]. A much greater challenge is the convergence of mobile connectivity, residential, and business services into one PON infrastructure, which provides the flexibility to empower services and applications envisaged in our proposal. This is a highly desirable feature in next-generation networks, as it reduces the cost of network ownership and allows extending the concept of convergence to the service level, in addition to the data plane [11]. Besides the need for interoperability among different technologies, there are a few open issues: 1) the inadequacy in ensuring diverse availability and guarantee of different levels of services over a shared infrastructure, 2) issues surrounding security, and 3) the lack of an effective business model and value chain capable of monetizing the higher flexibility provided by this framework.

Our proposed architecture is inherited from the DISCUS European FP7 project [12], although for the OFCity project, due to the limited optical reach, the first split stage might not require optical amplification. In addition, the first stage split could terminate some of the connections that require ultra-low latency, such as fronthaul/midhaul mobile signals. By placing the base band unit (BBU) near the first stage split, any latency issue due to optical transmission is eliminated, as the first stage split is typically within a few kilometers of the end-user. Ultra-low latency is critical for future services based on virtual reality and/or augmented reality that will underpin the kind of flexible city we envisage. It also will enable technologies such as cloudlets and mobile edge computing for dynamic provisioning of these services.

Ubiquitous high-speed mobile service is achieved through a combination of high-density deployment of cells and shared Wi–Fi connectivity. It is expected that cells will employ multiple transmission technologies, from LTE-A to Wi–Fi, Li–Fi, low power RF, and newer technologies as they emerge, using multiple parts of the wireless spectrum, spanning from hundreds of MHz to several tens of GHz. The cell density required for enabling functional 50 Mb/s user connectivity is of the order of 15 cells/km^2. Macrocells, covering a larger use base and thus availing lower traffic variation, will operate on backhaul, while smaller cells will operate on midhauling or fronthauling until midhauling becomes commercially available.

As previously mentioned, we believe the main focus should be on services and application, and the network underneath should be completely transparent to users. The user only interacts with the applications, which must work reliably and seamlessly as the user moves throughout the city. Such high reliability, reconfigurability, and fast handover between diverse physical layers will require an orchestration engine capable of reserving capacity through *ephemeral connections* [13]: on-demand end-to-end virtual connectivity guaranteeing personalized QoS only in place and for the time duration required by the application.

3) Business Model: Networks will never be transparent to users if the business model involves direct interaction between users and the network, such as users paying for network connectivity (as is the case today). Users should only pay for the services they use, because that is where the value resides, and not for the network usage. The revenue stream should follow the value chain of the application, going from user to the application provider to the network provider. Our hope is that users will not have to make decisions on the capacity to subscribe to but only on the specific services, which come with a service guarantee, i.e., by the use of a guaranteed ephemeral network connection.

In some cases, where for example the XGS-PON ONU cannot reliably guarantee certain services, the end user might be required to upgrade to an NG-PON2 compatible ONU or a high-speed point-to-point link.

One interesting if not bold outcome of our study is the change of network ownership structure. It is common to split the possible network ownership into three layers: passive network infrastructure (i.e., equipment such as ducts and fiber), active network infrastructure (equipment for transmission and switching), and service provisioning (i.e., by leasing capacity from the active network provider). A software-defined networking (SDN) layer can enable the active network provider to publish a set of APIs. These APIs will allow applications to interact with the network control system either directly or through the mediation of an orchestrator or service broker, thus potentially replacing the role currently held by service providers.

B. Team FIBRUS

By L. Valcarenghi (co-lead), D. R. Campelo (co-lead), Ph. Chanclou, V. Jungnickel, and H. Roberts.

OFCity broadband improvement is foreseen by 2020. With this horizon in mind, Team FIBRUS proposed a solution targeting the following objective: providing person-centered services and applications supported by ubiquitous high-speed Internet, wired when the user is stationary and fiber is available, and wireless for everything else. The fundamental architectural approach is to distribute fiber to the premises (FTTP) everywhere possible using existing conduits with systems such as Gigabit PON (G-PON), XGS-PON, 10 Gb/s Ethernet PON (10G-EPON), and NG-PON2. The remaining connectivity will be via wireless connections exploiting advanced functions, e.g., massive multiple input-multiple output (MIMO), coordinated multi-point (CoMP), and cloud radio access network (C-RAN), from the terminus of the optical fiber. Not only does this method save construction cost but also addresses the need for mobile services as broadband connections continue to evolve from wired to mobile wireless.

1) Services and Applications: A key service that we envision under the umbrella of person-centered services is personalized care, catering to the needs of individuals with disabilities, senior citizens, and the sick and injured. Another key service is self-driving connected cars [14], which will allow business people to work while commuting between home and office, enable millennials to safely post travel reports on social networks during their journeys, and, even more importantly, assist senior citizens, no longer capable of driving, to regain the freedom of travelling to where they want and when they want.

Wireless-enabled applications such as *Be My Eyes* [15] will involve social networking to help sight-impaired people to see what they buy at the stores. Remote patient monitoring will allow senior citizens to be better assisted at home and sportsmen to recover from injuries without traveling long distance for rehabilitation. Finally, the *Digital Clone* [16] will act as a personal assistant to reduce the burden of skimming e-mails and conducting repetitive business throughout the workday.

However, all the aforementioned applications present multifold requirements that a single flat broadband network architecture must be capable of satisfying. As depicted in Fig. 3, requirements of latency, bandwidth, and reliability can be loose, as for the Digital Clone, or very strict as the 10–100 ms latency range for vehicular networking applications [17], e.g., driverless cars, active road safety, traffic efficiency and management, and infotainment. Future machine-type applications may require even lower latency. Thus the proposed network must be capable of differentiating the QoS for each specific application while serving them all in parallel.

2) Architecture and Technology: To provide the envisioned person-centered services, a mixed solution will be required: 1) 75% of the OFCity broadband coverage will be via FTTP, and 2) the remaining coverage will be achieved through wireless connections and fiber to the antenna (FTTA). The proposed network topology is depicted in Fig. 4.

A ring topology, similar to the solution proposed by the project INCIPICT [18], is utilized as the OFCity metro aggregation network. The ring provides resilience to a single failure and offers bi-connectivity to the backbone network. In selected ring locations, optical line terminals (OLTs) are placed to connect not only fixed users in a FTTP solution but also to antennas for mobile applications. In addition, where construction is not possible, point-to-point wireless (e.g., millimeter-wave or optical) backhauling is used.

3) Business Model: Table III summarizes our budget plan.

The targeted OFCity improvement is to reach around 200,000 households (75% of total households) via FTTP with a budget of $75M. This implies a budget of $360 per household, which is a realistic cost for bringing fiber past the homes because the city has already installed

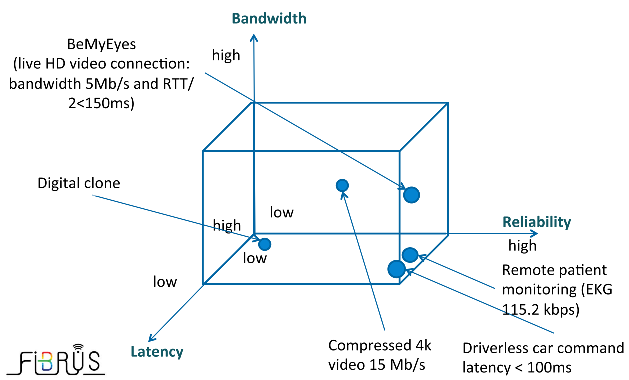

Fig. 3. Application requirements.

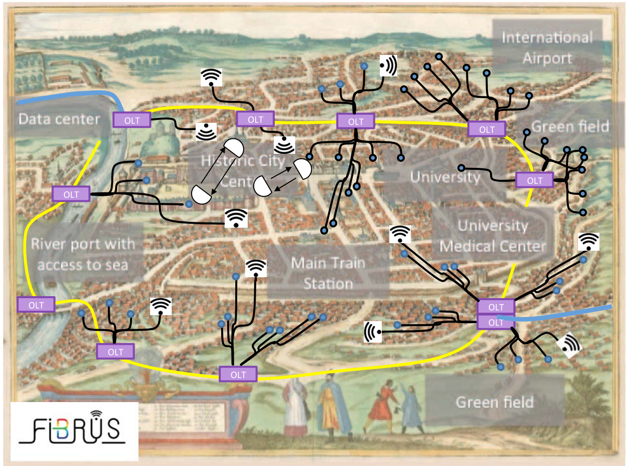

Fig. 4. Network topology proposed by Team FIBRUS.

conduit and is densely populated. The installation cost per home will be funded by a subscriber fee.

A budget of $40M is dedicated to the FTTA solution. It is assumed that, for the area of 400 km^2, around 100 macrosites can provide good coverage [19]. Total CapEx for macrocell coverage is about $10M, assuming $100k per macrosite [20]. By considering 10 outdoor and 50 indoor small cells per macrosite sector (typically a macrosite has three sectors), the numbers of outdoor and indoor small cells are 3000 and 15,000, respectively [19]. Actual costs for outdoor and indoor small cells vary widely depending on the specific deployment; see for example [20]. Here we assume costs of $5k and $1k per outdoor and indoor small cell, which lead to an overall budget of $15M including both deployments. The remaining $35M budget can be utilized to improve data centers in the metro ring.

Our solution considers both the aforementioned budget and the requested capacity per user, which is based on the EARTH project data prediction completed in 2012 [21]. The predicted capacity increases by a factor of 100 (50× increase in traffic and two users per household on average) to account for demand growth from the EARTH study period to the year 2020. Thus, the amount of capacity requested by 100% of heavy users in a dense urban area is about 9.2 Gb/s/km^2.

TABLE III
FIBRUS Budget Plan

Solution		Budget
FTTP (200,000 Households)		$75M ($360 per household)
FTTA	Three-sector macrosite (100 sites in 400 km^2)	$10M ($100k/macrosite)
	Outdoor small cell: 3000 units (10 units/sector)	$15M ($5k/small cell)
	Indoor small cell: 15,000 units (50 units/sector)	$15M ($1k/small-cell)
Data centers		$35M
Total		$150M

To support the OFCity area of 400 km^2, the overall capacity needed is 3680 Gb/s. Considering about 287,000 users (i.e., all the OFCity households plus private-sector businesses without including the population growth), the traffic per user amounts to 12.8 Mb/s. If we extend FTTP to 75% of the users, 33 OLT chassis are sufficient to cover all users, with 128 OLT ports per chassis and 50 ONUs per OLT port. Using G-PON technology at 2.5 Gb/s per OLT port, a 10,560 Gb/s overall capacity could be provided. Such capacity would allow OFCity to provide any user with 50 Mb/s each, far more than the projected 12.8 Mb/s. However, this traffic per user must be considered without any statistical multiplexing; therefore, the available peak capacity per user could approach 1 Gb/s. In addition, a graceful upgrade of the network can be done by adding an XGS-PON or NG-PON2 system.

For FTTA/wireless, if we consider the same traffic assumptions based on the EARTH study with a factor of 100× increase and that 25% of the overall users are served by FTTA, then the total capacity required is 2.3 Gb/s/km^2 after the initial rollout in 2020. Thus, about 180 users will share a 2.3 Gb/s capacity within an area of 1 km^2. In other words, each macrosite will provide 13 Mb/s capacity to each user without statistical multiplexing.

Similar to the fixed network, the available peak traffic for one wireless user could approach 100 Mbit/s or more. In order to attain this traffic capacity, radio interferences must be managed with techniques such as CoMP and massive MIMO by defining a flexible radio cluster comprising several macro and small cells. Centralized radio processing can be collocated with the OLTs. This type of deployment can simplify network organization and improve peak and average wireless traffics.

If more capacity is needed for wireless end users, emerging 5G technologies, more antennas and small cells can be utilized and supported by higher-speed PONs. Assuming that each site consists of 180 small cells and three macrocell sectors, each user could receive about 60 Mb/s via a 10 Gb/s PON to each site. With very small cells, we could have one user per cell on average. In this case, statistical multiplexing is not relevant per small cell but must be considered for the cluster of 180 small cells. Under this condition, the burst peak traffic for one user could approach 1 Gb/s.

In conclusion, the solution for improving the OFCity broadband network, as proposed by Team FIBRUS, consists of an upgradeable PON combined with advanced wireless technologies to enable mobile and advanced applications, such as the Digital Clone, autonomous cars, and, in general, person-centered services and care.

C. Team Ofconn

By R. Tucker (lead), L. Du, M.-C. Marinescu, C. Middleton, and S. Yin.

Ofconn recognizes the importance of connecting as many homes and businesses as possible via fiber, providing customers access to the best available broadband services, and enabling affordable future upgrades to higher capacity.

Team Ofconn noted the relatively low uptake of broadband services in the city to date. Therefore, we propose a community engagement program aimed at encouraging citizens to use the network and the city to leverage the network to enhance its services. Key benefits of the Ofconn proposal are as follows:

- *A Gigabit City*: Fiber to all premises by December 2020; data rates from 100 Mb/s to 10 Gb/s; free Wi–Fi in the city center, airport, and other public spaces; city services provided via a gigabit OFCity Intranet.
- *Community Engagement*: A $41 million community engagement program and OFCity Portal, innovation hubs for applications development and small-to-medium enterprises, sustainability and community focus, an energy supply to provide heating for the new city swimming pool development.
- *Network Plan*: OFCityNet, a wholesale broadband access network; a public private partnership (PPP); open access to encourage competition between retail service providers (RSPs).
- *Budget model* enables future upgrades and cost decreases.

1) Business Plan: The Ofconn business plan is structured to operate within the budget of $150 million, while achieving all the benefits listed above. To make this feasible, the revenue generated during the initial phase of the rollout will be used to assist construction in the later phases of the project and to help fund the community engagement program.

a) Financial model: The estimated cost for 100% fiber penetration is $180 million (Table II). Key financial parameters of our business plan are set out in Table IV.

b) Service offerings and take-up rate: Figure 5 summarizes the projected number of premises passed and wholesale service offerings until June 2021. The base service is a symmetrical (upstream and downstream) 100 Mb/s offering at a wholesale price of $25 per month. It is expected that this offering will initially support the most popular residential service. A symmetrical 1 Gb/s service will be priced at $55 per month, and a symmetrical 10 Gb/s point-to-point (PtP) service, aimed primarily at business customers, will be priced at $300 per month.

Ofconn has signed a memorandum of understanding with the incumbent telco in the city (OFT&T) under which OFT&T has agreed to migrate all of its present ADSL customers to FTTP, with a retail price for the 100/100 Mb/s service that is no higher than current ADSL prices. OFT&T will decommission its copper network when the fiber rollout is completed.

As shown in Fig. 5, a symmetrical 10 Gb/s service will be offered starting in December 2019, when the wholesale price of the 100/100 Mb/s and 1/1 Gb/s services will decrease to $15 and $30 per month, respectively.

Figure 6 shows the projected take-up rate until June 2021. We anticipate a rapid take-up of the 100/100 Mb/s service, as a result of OFT&T's plans to migrate the ADSL customers to the new fiber network. Other RSPs will be encouraged to compete with OFT&T at the retail level.

TABLE IV
KEY PARAMETERS OF OFCONN'S FINANCIAL MODEL

Available cash	$150 million
Total fiber CapEx	$180 million
Other CapEx	Fiber drops, metro network, Wi–Fi
OpEx	Rental of space in central offices, 10% service fee for Ofconn, power, software and hardware maintenance
Interest rate	0%

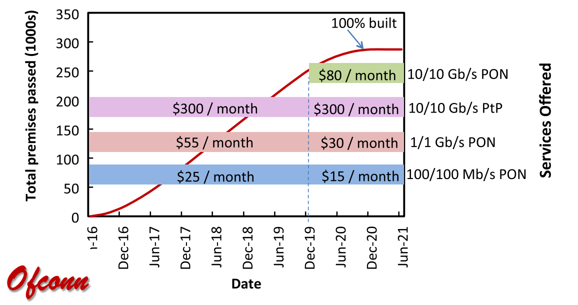

Fig. 5. Number of premises passed and wholesale service offerings until June 2021.

c) Budget projections: A cash flow analysis of the project is shown in Fig. 7. The cumulative cost of rolling out the fiber network reaches $180 million by December 2020. The cost of fiber drops to each premises rises to $100 million by the same date, and cumulative expenditure on the community engagement program and on network operational expenditure (OpEx) rise to $43 million and $64 million, respectively. Peak funding ($149.2 million) is reached in May 2020. Ofconn's profit margin will be set at a nominal 10% of OpEx.

2) Services and Applications: Ofconn believes that an all-fiber network will provide a foundation on which to build a more livable, inclusive, and equitable city. Given the assets of the city (university, hospital, data center) and the youthful age distribution of its citizens, the Ofconn Team will assist OFCity to leverage the wide availability of broadband to support education, training, and innovation.

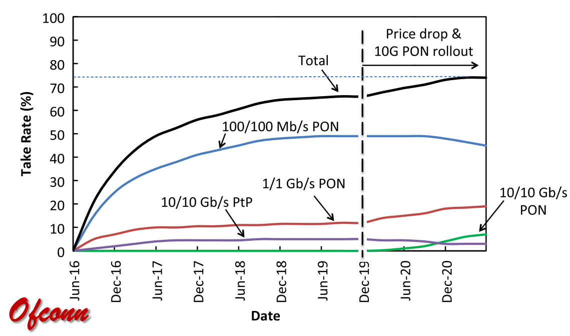

Fig. 6. Projection of take-up rate until June 2021.

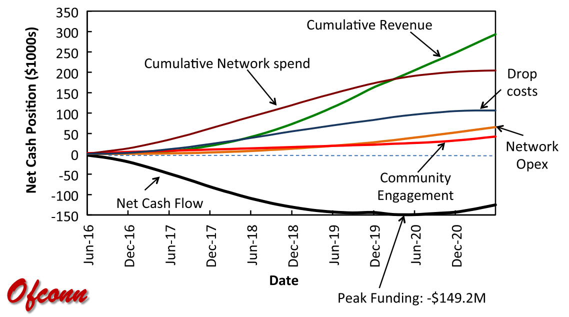

Fig. 7. Net cash position until June 2021.

Improved education opportunities will enhance the employability of citizens and assist the community to shape many aspects of OFCity life—from health care to sustainability.

Led by the Chief Digital Officer (CDO), and championed by the Community Leaders Digital Council, Ofconn will establish a Community Engagement Program (CEP) aimed at achieving high digital literacy across the population, fostering innovation, and attracting high-tech employers who will keep highly skilled university graduates in the city.

The CEP will employ 25 staff, to be headed by the CDO. Key aspects of the CEP will be the OFCity Portal and four innovation hubs. The OFCity Portal will use the OFCity Intranet to provide gigabit connectivity for all data transfers within OFCity, regardless of the tier of service purchased by users from their RSP. The OFCity Portal will provide the platform for *digital by default* delivery of city services, streaming contents of community events, and a software lending library.

Many aspects of city operations (including the locations of public transport vehicles, the state of vehicle traffic flows, and usage of public facilities) will be openly available on the portal. Citizens and businesses can make use of these data to offer services and to make informed decisions about their (quality of) life and issues affecting their community. The abundance of bandwidth and the free gigabit connectivity for local traffic enabled by the OFCity Intranet will foster a culture of (small) bandwidth-hungry startups that can test and tune their applications at an affordable price.

The four innovation hubs will offer a learning environment designed to develop basic digital literacy and encourage experimentation and the creative use of leading-edge technologies. Located in the city center, near the central train station, in the university neighborhood, and at the airport, the hubs are designed to expose people of all ages to the possibilities of abundant gigabit connectivity. Staff in the hubs will provide hands-on training in spaces where people can collaborate and learn from each other. For example, virtual reality learning experience is designed to make the learning process more interactive, more memorable, and more affordable to all OFCitizens.

3) Architecture and Technology: Figure 8 shows the conceptual OFCity network architecture. The RSPs connect to the wholesale network at the point of interconnect (POI), located inside the existing city data center. RSPs can rent space and power inside the POI to house networking gear, e.g., broadband network gateways (BNGs) for customer termination; routers for aggregation, peering, and cache management; IPTV distribution equipment; and transport to backhaul traffic to other networks. Multiple RSPs will connect through the POI, including large ISPs such as OFT&T and smaller niche players.

There are two separate handoff switches to enable larger ISPs to build a redundant network. Smaller RSPs may only want to use a single BNG and lease backhaul connections to peering markets. Ofconn, as a national ISP beyond OFCity, can provide these backhaul connections to the major peering sites.

The POI is connected to eight central offices (COs) through a ring-based network using an off-the-shelf optical line system (OLS) with an optical transport network (OTN) protocol.

We considered coherent-detection transceivers, e.g., CFP2-ACO, as well as direct-detection transceivers, e.g., QSFP28, as candidates for the OLS. The reach has to be at least 20 km to cover the 400 km^2 city, and the capacity per transceiver will be at the 100 Gb/s level, which will be needed to facilitate the potentially large Intranet traffic from residents and also enable 10 Gb/s PtP connections for both business and rapidly growing wireless x-haul services. Typical coherent transceivers, such as CFP2-ACO and CFP2-DCO pluggable modules, use narrow linewidth lasers and dual polarization I-Q modulators in the transmitter, and 90-degree hybrid and high-speed PDs in the receiver. Digital signal processing enables high bit rate with advanced modulation format, e.g., QPSK (100 Gb/s), and facilitates dispersion compensation, which makes the OLS robust within the range of OFCity. A key consideration is that coherent transceivers will ensure the network to be future proof given their easy upgradability to higher line rates with higher-order modulation formats, e.g., 16-QAM (200 Gb/s). Many design simplifications are in progress to further reduce the cost. Therefore, we decided to use coherent transceivers in the OFCity network.

In the access network, conventional TDM-PON architecture is deployed with an evolution path from G-PON (2.5/1.25G) to XGS-PON (10/10G) and eventually reaching the NG-PON2

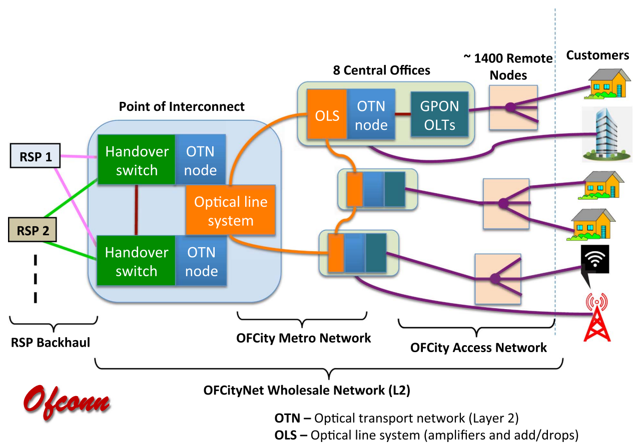

Fig. 8. OFCity network architecture proposed by Ofconn.

stage (40/40G). More than 1,400 passive remote nodes (RNs) are deployed to support different types of end users, e.g., residential, business, Wi–Fi access, and wireless x-haul end points (cellular tower). Each RN is connected to the end users and the nearest CO. Optical power splitters are housed inside the RN to split the signal for the TDM-PON residential and small business customers. Large businesses and wireless x-haul users requiring consistent bandwidth can purchase PtP services bypassing the optical splitter at the RN.

The OFCity Intranet is supported through Layer 2 by using a MAC filter that tracks ONUs. Traffic starting and terminating at Ofconn-issued ONUs will not be handed over to RSPs but routed straight through the OFCity Layer 2 network. A small-scale data center (DC) connecting to this Layer 2 network and the RSP networks will provide small local developers with inexpensive resources to develop cloud-based applications.

The POI is located on the western side of the river in the city's existing DC, turning a part of it into a carrier hotel. As an added benefit, a new public swimming pool can be heated by the heat generated from the DC. Two different river crossings are used to prevent the DC from being cut off from the city.

In conclusion, this proposal from Ofconn provides excellent value for the $150 million investment. Fiber connectivity will extend to all homes and businesses in OFCity, with a variety of service levels and wholesale pricing that enable retail service providers to offer attractive service plans. The community engagement program, through the OFCity Portal and innovation hubs will play a major role in transforming OFCity into a hotbed of digital innovation.

D. Team TERAPOLIS

By D. Simeonidou (lead), S. Figuerola, T. Takahara, and R. Yadav.

Given the challenge of designing a future smart city, OFCity, Team TERAPOLIS did not take it as a way of designing a network infrastructure with the most technical buzzwords but as an opportunity to make the city a regional hub of innovation and the most livable place that can attract various businesses and residents. We started with researching the needs of citizens who may live in such a city and what makes the city attractive for new citizens and businesses to move in.

This perspective allowed the team to consider the applications and services citizens may need and to design an open and scalable network, which can evolve with the ever-changing demands. In our proposal, the future-proof and open network infrastructure includes providing fiber access to as many premises as feasible, while optimizing the cost of deployment by utilizing wireless technologies especially in locations where deploying new fiber would be expensive, e.g., buried outside plants.

1) Services and Applications: Our proposal provides a blueprint for a secure, agile, reliable, and livable city focusing on the quality of life of its citizens toward the smart citizen concept. The proposal allows for services created and delivered by users to support a smart, healthy, efficient and happy society. This includes transport on demand, pollution monitoring and control, e-health and e-government applications. Typical services could be, for example, 4k and 8k streaming from surveillance cameras requiring 40–100 Mb/s per stream and connected cars needing 100 Mb/s.

For businesses, our proposal provides an ecosystem for prototyping and testing new services and applications with low barriers to deploy smart technological innovations by utilizing flexible and affordable network cloud infrastructure. To improve the service performance, edge-computing solutions are also considered to perform analytics at the network edge without the need to centralize all the computing in one unique place.

2) Architecture and Technology: Our vision is to create an open and standard-based infrastructure as depicted in Fig. 9. This open approach makes use of the SDN concepts and allows for multi-technology support with technology-agnostic control and management by abstracting the underlying hardware components. This open approach also allows for a multi-tenant solution by dynamic resource sharing through virtualization of the computing and network resources.

Given the characteristics of typical applications and services to be supported and keeping future-proofing the deployed network infrastructure in mind, the primary goals for our network architecture design are to provide

- over 1 Gb/s services to the residential market utilizing existing infrastructure whenever feasible;
- up to 10 Gb/s (and higher in the future) to business customers;
- scalable and cost effective solution for smart city infrastructure such as sensors, camera, smart cars, macro and small cell cities, Wi–Fi, etc.;
- redundant WAN connectivity to nearby smaller cities as well as to national backbone network;
- convergence with future 5G services.

Figure 10 shows our proposed high level network architecture for OFCity. This architecture builds around two data centers as the hub of the network, which hosts the cloud and control infrastructure. These two data centers serve as the redundant and scalable backbone of the city's

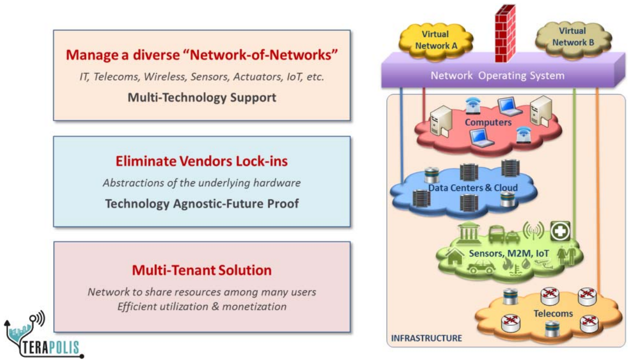

Fig. 9. Open infrastructure for innovation (courtesy of Zeetta Networks, www.zeetta.com).

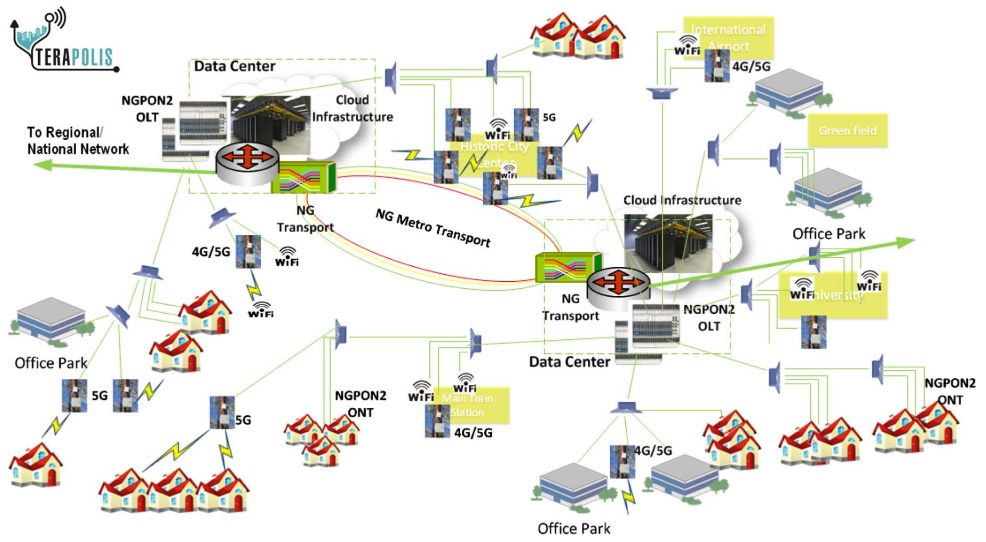

Fig. 10. High-level network architecture proposed by Team TERAPOLIS.

smart network as well an interconnection to regional and national network backbones. This design also enables more efficient fiber deployment reaching all parts of the city. The data centers would be interconnected through a next-generation ROADM transport network that can scale with the demand of the traffic.

As for connectivity to residential and business premises as well as to smart infrastructure, we envision the use of NG-PON2 and wireless technologies. PON technology enables the optimal use of fiber infrastructure, which is shared across multiple customers, as well as reduced deployment cost and increased reliability as only passive components are used in the outside plants. The NG-PON2 technology further provides opportunity for a flexible and scalable pay-as-you-grow deployment model to keep pace with future bandwidth demand. NG-PON2 currently supports up to 10 Gb/s bandwidth to individual customers with potential to grow beyond 10 Gb/s per customer through channel bonding of multiple wavelengths.

For business broadband access, we plan to deploy fiber to all the business premises. For residential broadband access, 50% of households would be passed with fiber. For the rest of the households, which are served from buried distribution plants where fiber deployment is terminated, we would use 5G wireless technology to provide the *wireless drop* for up to 1 Gb/s bandwidth. NG-PON2 would be utilized as the backhaul for the 5G cell locations at the distribution point. This strategy allows us to optimize the available budget for fiber deployment because the cost of fiber deployment in the buried distribution plant is generally three to four times higher than an aerial distribution plant.

The coverage in the historic city center (1 km × 2 km) would be provided through a combination of 5G and Wi–Fi to avoid any digging in this area. Similarly, 4G/5G and Wi–Fi coverage would be provided across the city in public locations to serve various smart infrastructure elements.

Figure 11 depicts the SDN control and virtualization platform for an open vendor-agnostic network and information technology infrastructure planned as part of the TERAPOLIS proposal. This should facilitate agility in network operations and rapid deployment of new services through dynamic resource sharing by virtualization of the computing and network resources.

3) Business Plan: Through the use of optimized fiber deployment and intelligent technology choices, 50% of the available budget ($75M) would be utilized to deploy fiber to 100% of business premises and 50% of the residential premises as well as fiber to the distribution point for the remaining 50% of residential premises. The rest of the budget would be divided among data center infrastructure for hosting, refurbishing of lampposts for fiber, wireless hosting, and sensor RF mass connectivity. We also plan to set aside a budget for business to encourage innovation to develop unique services for the citizens and businesses.

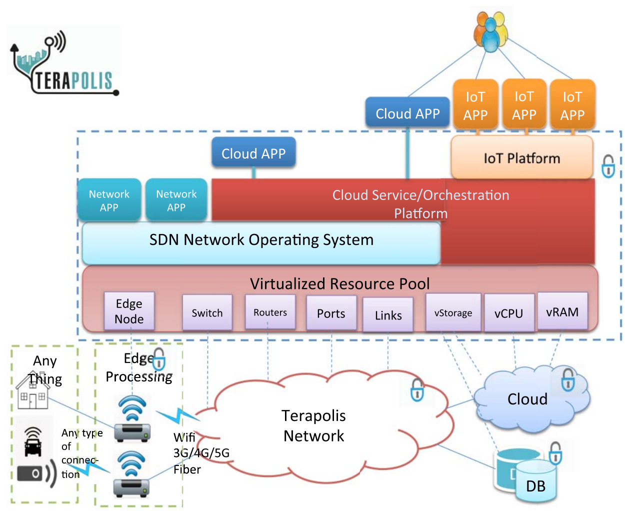

Fig. 11. SDN controlled infrastructure (courtesy of Bristol Is Open, www.bristolisopen.com).

In summary, Team TERAPOLIS' proposal focuses on a technology-agnostic and future-proof network infrastructure and an open, programmable software/hardware architecture to enable innovations and support a livable and resilient city that can grow into a hub for high-tech businesses. An investment in this infrastructure can provide a high return on investment while setting up the basis for a smart citizen ecosystem.

IV. Conclusion

A competition of multidisciplinary teams with a discussion in a final workshop at OFC was used for the first time as a process to generate novel ideas and perspectives on a future infrastructure in a typical medium-size city.

The service examples given by all teams show that investments in a modern communication infrastructure can meet with important strategic objectives of the city government. It can make the city attractive for a wide demographic variety ranging from the enablement of new social applications for youngsters and millennials, to facilitating e-health, care, and remote presence for the elders. A low latency network will provide the backbone for the Internet of Things (IoT), sensors, or safe traffic with driverless cars. An ultra-broadband network combined with a local data center or scalable connections to the cloud is also an economic enabler to grow existing or new businesses. This could be further stimulated by reserving a budget for a community engagement program.

The winning team proposed a complete FTTH installation as a future safe infrastructure. They showed the implementation could be economical by leveraging a partnership with an incumbent service provider and using a wholesale business model. Other teams brought up the need for high-density and high-capacity wireless services, which will require a high bandwidth fiber backhaul network. The latest copper access technologies, which are capable of multiple gigabit/s over short strands of less than a hundred meters twisted pair or coax, as well as wireless solutions, were considered valuable for areas where rollout of fiber was too expensive or troublesome, e.g., in the historic city center. Several teams pointed out that SDN and cloud infrastructure for scalable implementation of network function virtualization (NFV) or applications are mandatory to operate a connected infrastructure.

It is notable that the four teams presented a diversity of solutions involving a range of access technologies from low-speed copper to high-speed wireless. Further, the applications presented by the teams were shown to have disparate and competing network requirements. As pointed out by one of the teams, future access networks may be directly application-driven, and the design principles used to construct such a network may well be different from the ones used today.

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