 doi:10.20944/preprints202012.0064.v1

Article

Sustainable and Reliable Information and Communication Technology for Resilient Smart Cities

Nikolay Tcholtchev[1,*] and Ina Schieferdecker[2]

1 Fraunhofer Institute for Open Communication Systems (FOKUS); nikolay.tcholtchev@fokus.fraunhofer.de
* Correspondence: nikolay.tcholtchev@fokus.fraunhofer.de; Tel.: +49 30 3463-7175
2 Federal Ministry of Education and Research, ina.schieferdecker@web.de

Abstract: Information and Communication Technology (ICT) is at the heart of the Smart City approach, which constitutes the next level of cities' and communities' development across the globe. Thereby, ICT serves as the gluing component enabling different domains to interact with each other and facilitating the management and processing of vast amounts of data and information towards intelligently steering the cities infrastructure and processes, engaging the citizens and facilitating new services and applications on various aspects of urban life - e.g. supply chains, mobility, transportation, energy, citizens' participation, public safety, interactions between citizens and the public administration, water management, parking and many other use cases and domains. Hence, given the fundamental role of ICT in cities in the near future, it is of paramount importance to lay the ground for a sustainable and reliable ICT infrastructure, which can enable a city/community to respond in a resilient way to upcoming challenges whilst increasing the quality of life for its citizens. This paper constitutes a continuation of a series of research documents and standardization activities, which relate to the concept of Open Urban Platforms (OUP) and the way they serve as a blueprint for each city/community towards the establishment of an ICT backbone. Thereby, the current paper emphasizes on the aspects of sustainability and resilient ICT, whilst reporting on our latest activities and related developments in the research area.

Keywords: Smart City, Urban ICT, Open Urban Platforms, Sustainable Cities, Resiliency, Quality Assurance

1. Introduction

Smart Cities and Communities[1] are at the forefront of innovation, research and development in modern societies. As of 2020 more than 50% of the world population lives in cities [1] with a tendency for a dramatic increase in the percentage of urban population within the coming years [1]. Hence, there is an urgent need to optimize the processes within a city/community and to push for new eco-systems generating novel business and operational models for increasing quality of life for citizens, whilst at the same time reducing costs and improving the city/community processes and operations. Thereby, ICT[2] plays a vital role in enabling such eco-systems given that they will emerge around the notion of data/information gathering, and making this data/information available across multiple domains towards the combination and exploitation of synergies amongst various aspects of urban business and everyday life. A Smart City naturally emerges around an Urban Data Platform, which consolidates various data sources across an urban eco-system. Indeed, the data sources can be versatile including static data – e.g. governmental data, Open Data in general, and any sort of city

[1] Subsequently, we use the term Smart City as shorthand for Smart City and Community.

[2] ICT stands for information and communication technologies.

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data/information that does not constantly change its value/parameters – and dynamic data, e.g. continuous real-time data like sensor/IoT[3] data, global positioning data, etc. In order to facilitate such a data driven approach, various components, network segments, and computing nodes from different silos and domains need to interplay efficiently towards enabling a data driven Smart City. This includes sensors generating and sending data over belonging gateways, which in turn forward the sensor data over telecom/Internet type of networks to data nodes at the network edge or data centers in the cloud. In addition, different services and applications - including mobile and embedded - utilize the data, analyze it and generate added value for end users, citizens, city decision makers and further stakeholders within an urban environment.

Along these considerations, it is of paramount importance to establish a holistic approach to the ICT in a Smart City. This holistic approach should serve as a blueprint for establishing an urban ICT infrastructure and should enable the creation of dynamic and versatile eco-systems of large industry, small-mid size enterprises, start-ups, public sector, open source community, non-governmental organizations, applied research institutes, universities and city administration. Such a holistic approach can be designed based on a reference architecture, which leans on other reference architectures coming from domains such as telecommunications (e.g. ISO/OSI[4], TMN[5] and others) or Internet data-based communication (e.g. TCP/IP[6] and others). Such reference models have enabled the rapid growth of voice and data communication across the world and have led to one of the most impressive success stories of human kind – the Internet. Indeed, as the Internet and the telecommunication domain in general has proven to have developed in a sustainable and resilient way, we envision the same for the emerging ICT infrastructures within cities and communities that will serve as the backbone of future societies. There are various aspects that enabled the sustainability and resiliency in the case of the Internet including the belonging (1) reference architectures, the (2) quality assurance and certification procedures, the corresponding (3) standardization activities and the (4) systematic approach to components, systems and networks integration and interoperability. Within Smart Cities, these tasks are far more challenging given the plethora of technologies (including legacy technology), data models, communication protocols, components, modules, providers, vendors, use cases, stakeholders, application domains, services and users, which are involved and should be considered.

The main goal of this paper is to combine the reasonable features from multiple approaches to ICT reference architectures and to show how these can be used to define a sustainable and resilient ICT infrastructure within a city/community. Such a reference architecture for ICT in Smart Cities emerged from the activities of established standardization groups such as the German DIN 91357 [4][15], which is based on the European Innovation Partnership (EIP) and the Memorandum of Understanding (MoU) on Sustainable Cities and Communities (SCC) [6] [5] and its belonging ICT reference architecture work stream. In this context, we also discuss a quality assurance approach –

[3] IoT stands for the Internet of Things.

[4] ISO/OSI is the Open Systems Interconnection (OSI) Reference Model of the International Organization for Standardization (ISO).

[5] TMN stands for Telecommunications Management Network defined by the International Telecommunication Union Telecommunication Standardization Sector.

[6] TCP/IP is the Transmission Control Protocol/Internet Protocol defined by the Internet Engineering Task Force (IETF).

oupPLUS[7] (initially presented in [34] [36]) – and detail the way it can be used to provide an interoperable, secure and resilient ICT. Furthermore, we outline key technological pillars which should be considered in each Smart City development plan and for which oupPLUS is meant to provide the means for quality assurance, resilience and sustainability.

The rest of this paper is organized as follows: Section 2 reviews various related research and development activities including long-term initiatives such as FI-WARE[8] or European projects such as Triangulum and Espresso. The following Section 3 provides the basic definitions of Sustainability, Smart Cities and Sustainable Smart Cities thereby setting a frame around the discussions and elucidations of the current paper. Section 4 presents the concept of reliable ICT and motivates it through some historical definitions. The next Section 5 sets the ICT frame for further discussions by presenting the concept of ICT reference architectures and Open Urban Platforms, which is the natural setting for the development of a Smart City and enhancing its reliability. Section 6 shows the importance of quality assurance within urban ICT and proposes a special ICT reference architecture that provides the necessary constructs for systematically achieving a high degree of quality assessment and certification for Smart City technology. Section 7 presents key technological developments of relevance for future Smart Cities and places them in the framework of an Open Urban Platform. The final two Sections 8 and 9 depict the recommendations and next steps for achieving reliable and sustainable Smart Cities, thereby concluding and wrapping up the paper.

2. Related Work

A large number of Smart City solutions have been developed across European and German cities in the past years. [39] [38] and [40] are some examples of our previous work from the domains of mobility and energy, which enable the sharing of resources (e.g. car and bike sharing) as well as the optimized utilization of energy sources subject to certain economic and ecological goals. However, we can observe that the digitalization and optimization of urban processes is at stake, since it has reached limits, when it comes to single institutions providing smart services in a city. Hence, it is obvious that a horizontal approach is required that will break the various silos and facilitate the collaboration between different stakeholders, players and citizens within an urban environment. The driver behind this horizontal approach is clearly the ICT, which should aim at exposing various types of data and enabling the exchange of information between a large number of currently involved and potential players in an urban environment. Hence, it should not only optimize existing courses of action, but it should also provide a platform for the creation of future processes and use cases aiming at improving quality of life in future Smart Cities.

In order to achieve such a horizontal approach, a number of reference models were proposed within the past years, e.g. the EIP SCC one [5], DIN OUP [4][15][29][30], the H2020[9] Espresso reference architecture [25][28], the reference architecture from the FP7[10] STREETLIFE project [41],

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[7] oupPLUS stands for a quality-oriented extension of open urban platforms defined by DIN 91357, the German standardisation institute.

[8] FI-WARE stands for Future Internet-ware.

[9] H2020 is the European research framework Horizon 2020.

[10] FP7 is the European research framework programme 7.

the IoT based reference model of [45], the corresponding model from the H2020 Triangulum project [26] [24] [27] and further. These models in general structure the city in layers that reflect the various levels of information processing starting from the data sources, continuing with the communication network, the cloud/edge databases and the belonging data analytics up to the level of applications and services, which emerge based on these data processing chains. Many of these reference architectures come up with design principles such as open interfaces, open standards, open source, open data and artifacts that aim at avoiding vendor lock-in and creating viable local eco-systems for ICT developments and innovation.

Particular solutions implementing aspects of the above reference models are given by FI-WARE [35], UrbanPulse [44], DKSR[11] [43], CKAN/DKAN[12] [32] [33], MindSphere [42] and many others which are currently being systematically examined in a Fraunhofer FOKUS study financed by the Morgenstadt [37] Smart City community in Germany. Thereby, a number of over 60 different commercial and open source urban platforms are examined in terms of their compliance to the key features of the above listed reference architectures and with regard to their openness and capability to enable Smart City eco-systems (including SMEs, open source initiatives, industry, and academia).

Beyond the aspect of “reference architecture”, a large number of data models and communications protocols are of particular relevance for the ICT of a Smart City. First of all, the standard protocol suites of the Internet are of particular relevance – these suites include protocols such as IPv4/v6, OSPF, RIP-ng, BGP, DiffServ, IntServ, ARP, ND, DHCP, DNS, NTP, HTTP, SOAP and others, which ensure fundamental network functions of forwarding, routing, QoS and name resolution to name some (see e.g. [46]). In the IoT access network segment, relevant protocols are given by ZigBee, IEEE.802.15.4, 6LowPan and LoRaWAN whilst the over spanning IoT architectures utilize means like CoAP and MQTT (see e.g. [47]). All these protocols are based on well-defined non-proprietary standards enabling the open communication network exchange within a Smart City. The communication networks carry data using data/information models such NGSI-LD, SensorML, DCAT-AP as well as different linked data based formats describing the data and information within a Smart City (see e.g. [48]).

3. Sustainable Smart Cities

This section presents fundamental concepts for Smart Cities and provides working definitions.

2.1 Definition: Sustainability

There are a large number of definitions for Sustainability in literature. [17] provides e.g. a summary and overview of definitions from social and environmental perspective. Many of the definitions are not straight forward but aim at discussing and putting things in various perspectives as to encompass all relevant aspects for a particular field. In view of ICT for Smart Cities and Communities we use the term in the following sense: *“Sustainability is the capability of a system to exist in the long term based on its modularity, flexibility and intensive interaction and balanced exchange with its eco-system/environment”*.

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[11] DKSR stands for Data Competence Center for Cities and Regions.

[12] CKAN/DKAN stands for Comprehensive Knowledge Archive Network / Drupal-based open data portal based on CKAN.

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Yet, the overall term of Sustainability has been structured along the Sustainable Development Goals (SDGs), which are illustrated in Figure 1. The SDGs were defined by the United Nations in 2015. Significant progress in this regard needs to be achieved by 2030 [16].

Figure 1: Sustainable Development Goals according to [16]

Herein, *SDG 11* is directly framed to be *Sustainable Smart Cities and Communities*. In addition, ICT for Smart Cities can directly contribute to *SDG 9 – Industry, Innovation and Infrastructure*, *SDG 8 – Decent Work and Economic Growth*, *SDG 12 – Responsible Consumption and Production*, and *SDG 7 – Affordable and Clean Energy*, and indirectly to *SDG 1 – No Poverty*, *SDG 2 – Zero Hunger*, *SDG 3 – Good Health and Well-Being*, *SDG 6 – Clean Water and Sanitation*, *SDG 13 – Climate Action* and *SDG-16 - Peace, Justice and Strong Institutions*. An increased utilization of ICT within Smart Cities and Communities can positively influence a number of key areas such as mobility, (renewable) energy, health, transportation, water-management, waste-management, circular processes, public administration, or public safety and thereby contributing in parallel to job creation, economic growth, increased quality of life and poverty reduction. Hence, we believe that ICT based Smart Cities and Communities are to be seen as a means for achieving the above listed SDGs [49].

2.2 Definition: Smart Cities

According to [29],[30], and [31], a smart city/community is:

1. **intelligent**
2. **sustainable**, but also
3. **adaptable** meaning that it can adapt its action and process options according to social and/or economic needs,
4. **user-oriented**, that means that the citizens of a municipality are at the center of attention; satisfying their needs and optimizing related processes and services using ICT is the main goal of a smart city/community
5. **responsive**, that means that both the administration and the optimized processes and ICT services are in constant interaction with the citizens of a smart municipality

6. **sensitive** - using various types of sensor technology and data acquisition tools, a constant attempt is made to scan the situation and obtain the relevant data and to use it for new types of services, applications and process control options, and
7. **innovative**, which means that the smart city/community creates an ecosystem in which constant innovation - based on data, information, networking and modern ICT - continuously optimizes and improves urban efficiency and the quality of life of citizens.

2.3 Definition: Sustainable Smart Cities

In conclusion of the above, a Smart City needs to be intrinsically sustainable. We perceive a Sustainable Smart City as one that aims at fulfilling the corresponding SDGs and tries to achieve this in a sustainable way, and based on a sustainable infrastructure. This means, the processes and infrastructures of a city/community should work in a way as to achieve the SDG goals. It should be designed to be modular, flexible and able to successfully deliver results also in long-term, in correspondence to latest technological developments as well as social and environmental requirements.

4. Reliable ICT

In this section, we relate the requirements on the urban ICT of a Sustainable Smart City to the methods and means to make urban ICT reliable, dependable, and in result trustworthy, such that it can constitute the infrastructural basis of a Sustainable Smart City.

4.1 Definition: Reliability

Similarly to the term Sustainability, the notion of Reliability has been subject of many different definitions which are overlapping to a large extent and mostly reflect similar aspects in different domains. Furthermore, Reliability can also be seen as an attribute of Dependability as we are going to briefly discuss in the next subsection.

According to the Cambridge online dictionary, the term Reliability is defined as follows: *"the quality of being able to be trusted or believed because of working or behaving well"* [18]. With respect to information and communication systems, which are at the heart of a Smart City, the following definition is preferred – *"Reliability is defined as the probability that a product, system, or service will perform its intended function adequately for a specified period of time, or will operate in a defined environment without failure."* [19] This defintion originates from the American Society for Quality (ASQ) and has a more technical perspective. Hence, by applying this definition to the ICT infrastructure of a Smart City, we put the reliability requirements in context.

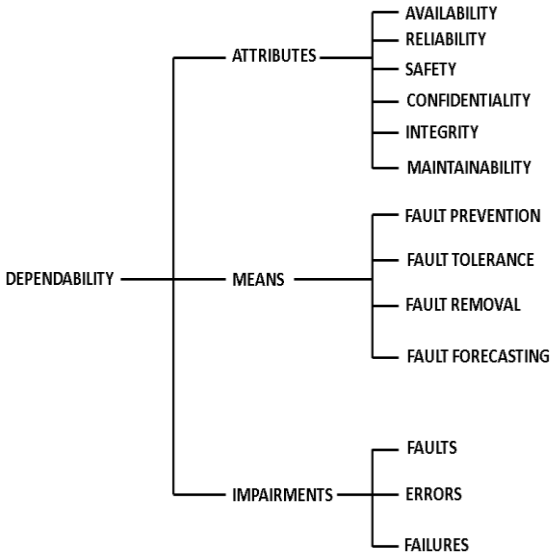

Figure 2: Structure of the Dependability Concept according to [20]

4.2 Definition: Dependability

The term Reliability can also be seen as an attribute of the overarching concept of Dependability, which is important in the area of distributed systems and communication networks. Dependability and dependable systems have been discussed in many fundamental research works [20][21][22][23]. Thereby, Dependability encompasses the various types of non-functional requirements for designing high-quality systems as well as the means to achieving these requirements and the major threats or impairments in the ICT context. [20] provides a comprehensive illustration of the key components comprising Dependability (see Figure 2). This includes among others key security aspects such as Availability, Integrity and Confidentiality. They play a vital role for urban ICT since only trustworthy processes and infrastructures will be adopted widely.

4.3 Quality Assurance for ICT Technology

In view of trustworthiness as well as of effectiveness and efficiency, quality assurance for urban ICT is essential for achieving reliable ICT components for Smart Cities. There has been intensive research on this topic in the past decades. Along this, the industry has established processes for quality assurance of single components, systems and of the overall systemic approach. Essentially, *quality assurance* addresses two main aspects: 1) the processes when developing/creating complex systems and 2) the testing of complex systems for deployment and operation, which ideally should take place in parallel to the development processes. Testing comprises various validation and verification activities for ICT and constitutes the most important quality assurance method in industry [50]. In testing, it is important to address different functional and non-functional perspectives on single components as well as on complex urban ICT systems as a whole. Testing approaches include conformance testing (i.e. the conformance to standards and requirements), interoperability testing, load and performance testing, security and penetration testing as well as usability and acceptance testing [51]. All these facets need to be delivered by urban ICT infrastructures on a reasonably high level, in order to guarantee the success of the intended introduction of Smart City development principles. These aspects are central for the reliability and resilience of the ICT infrastructure acting as a Smart City backbone.

5. ICT Reference Architectures and Open Urban Platform for Smart Cities

Reference architectures are seen as propositions for blue prints of the ICT infrastructure in Smart Cities. ICT reference architectures have been developed along the concept of Open Urban Platforms (OUP), which has initially been worked out on European level [5] [6] and subsequently standardized [4] by standardization bodies such as the DIN in Germany. OUP is a special type of blueprint that postulates a very high level of openness for urban ICT by prescribing the utilization of open interfaces and open standards for the data/information exchange between infrastructure components, systems and processes in a Smart City. Furthermore, OUP advocates the usage of Open Data and Open Source as key data sharing and code transparency principles. However, these two principles are mere recommendations as opposed to the open interfaces/standards requirement that is the key prerequisite for establishing an ICT infrastructure in conformance to OUP.

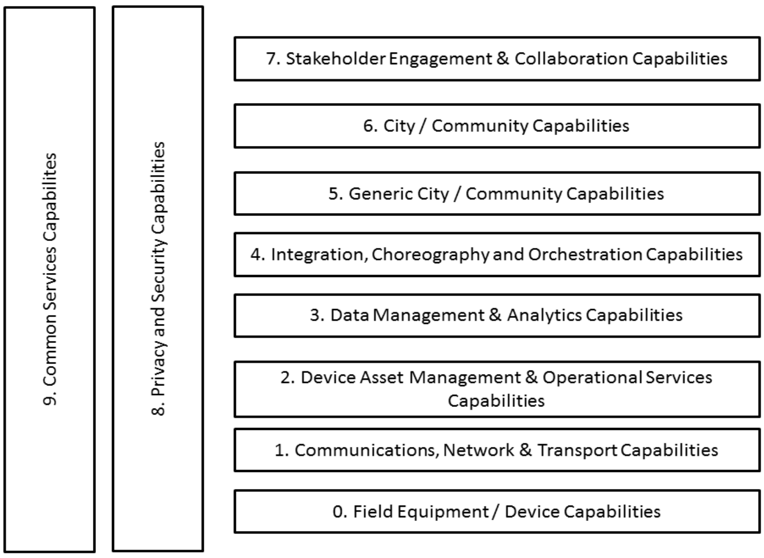

Figure 3: High-level View on the Open Urban Platform Concept as defined in [4] and [5]

Further tasks of an urban ICT reference architecture include the provisioning of a unified view on the ICT strategy of the city in question, as well as by the elucidation of the interfaces between the various technological layers and components within a city. Another important aspect is the need to be able to accommodate existing systems under the overall umbrella of an ICT reference architecture. Especially within the scope of open urban platforms, one of the main goals is the intend to enable the replication of Smart City solutions across cities thereby creating an ecosystem and a new market in order to boost Smart City approaches in terms of functionalities, deployments and applications.

Figure 3 provides a high-level view on the standardized Open Urban Platform concept. The overall structure is constituted by a set of layers describing the information processing paths within a city, roughly starting from the data sources (e.g. sensors), continuing with the communication network that enables the overall city interconnectivity, the databases and cloud infrastructures in the backend and the services which utilize the urban data in order to provide added value to various stakeholders such as the city/community, companies and the citizens. The overall layered structure is accompanied by cross-layer aspects relating to privacy and security as well to the management of the overall infrastructure and its common services.

The detailed OUP definition in [4] provides a large number of so-called capabilities for each layer/pillar that basically capture the functionality and the aspects which are implemented in this layer/pillar. Examples of such capabilities are given by *(Complex) Event Processing* and *Metadata Management* for the *"3. Data Management & Analytics Capabilities"* layer or by *Sensoring & Measuring* and *Time and Position Keeping* for the *"0. Field Equipment / Device Capabilities"* layer.

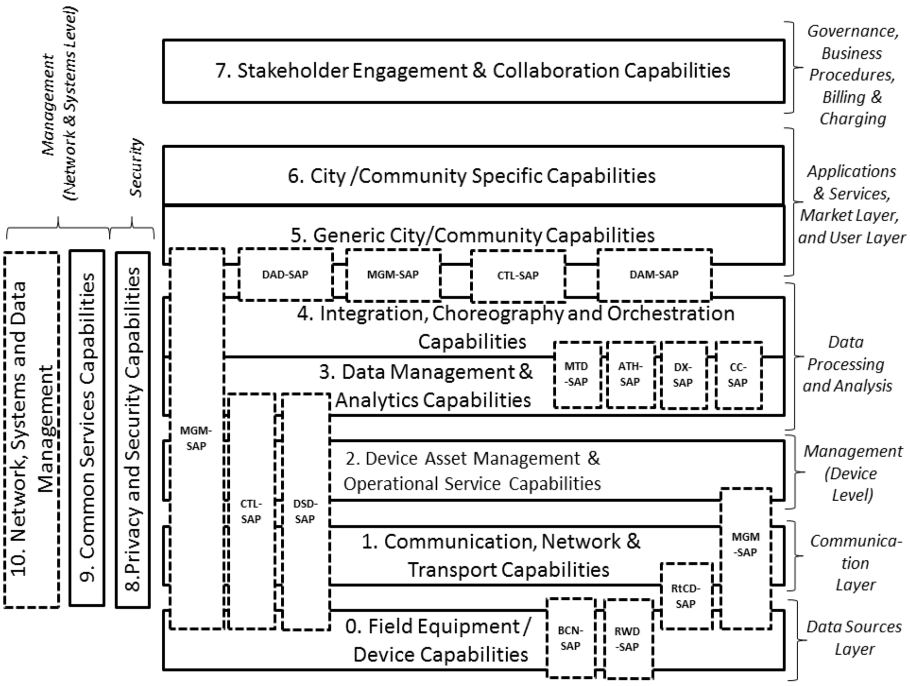

Figure 4: The oupPLUS Architecture as defined in [36]

6. oupPLUS: The Quality Assurance View on Smart Cities

oupPLUS (see [36] and [34]) is an OUP-based ICT reference architecture for Smart City, which has been developed at Fraunhofer FOKUS in Berlin. oupPLUS aims bringing together the insights from DIN SPEC 91357, EIP SCC Reference Architecture, the reference model from the H2020 Triangulum project [24] [26] [27] as well as the reference architecture definitions from the H2020 Espresso project [25][28]. Thereby, the Fraunhofer FOKUS researchers – having a strong background in the topic of quality engineering for ICT systems – bring in many aspects, which enable the systematic oupPLUS based quality process towards establishing a reliable ICT backbone for a city question.

The overall holistic illustration of oupPLUS is provided in Figure 4. It can be clearly observed that oupPLUS resembles many of the layers Open Urban Platform in addition to emphasizing on the key principles of open interfaces and open standards. Beyond this, oupPLUS aspires towards the identification and specification of abstract open interfaces as extensions to the reviewed and unified architectural principles of the considered research and standardization results. Thereby, oupPLUS aims to establish guidelines for well-defined open interfaces between the different ICT components and layers of an ICT Smart City backbone. This opens a variety of new opportunities for the Smart City development across the globe, such as 1) interoperability of different solutions in various areas and urban environments, 2) replication and reuse of Smart City solutions across multiple cities, 3) the creation of a viable ICT eco-system in cities/communities including the participation of small and medium-sized enterprises, 4) the increased utilization of Open Source, 5) avoiding vendor lock-in and last but not least 6) the systematic quality assurance of ICT components, solutions and complex systems within/for a Smart City.

The above-mentioned abstract open interfaces are constituted by the SAPs in Figure 4. The term SAP was borrowed from the Internet/telecommunication domain (especially TCP/IP and ISO/OSI) and stands for Service Access Point. Indeed, the SAPs of oupPLUS stand for abstract interconnections between various layers with their belonging capabilities and instantiating components in a real urban ICT instantiation of oupPLUS. Thereby, the SAPs would normally connect between modules/components/services and hence a particular instantiation of an SAP is given by a whole communication stack instance including a physical-, link-, network- and service-layer protocol, such as Ethernet/IPv6/TCP/HTTP/DCAT-AP to give an example. More detailed descriptions on the single SAPs are provided in [26]. However, in Table 1 we provide a brief introduction of the SAPs from Figure 4 and list relevant protocols stacks and standards which can play a role within a Smart City ICT back-bone. Furthermore, the information in Table 1 already hints on how oupPLUS can be used as a concept for Quality Assurance, namely by simply "testing the SAPs" which automatically means the testing of the relevant protocol stacks. In this setup, all possible types of test examinations – conformance- , interoperability- , security/penetration-, load- and performance-testing – can be executed leading to the systematic approach to high quality ICT components and complex systems. The aspect of Quality Assurance is further detailed in section 7.2.

Table 1: SAPs and Example Protocol Stack Instantiations

SAP-Name/Description	Protocol/Protocol Stacks/Standards
CTL-SAP: Control SAP	Cloud Control Protocol (Stack): 1) OpenStack Rest API + [HTTP/IP/...], 2) SOAP [HTTP over TCP/IP] /alternatively over UDP, 3) CORBA [IIOP over TCP/IP], 4) HTTP(S) / [TCP + TLS] / WiMAX or UMTS or LTE or WiFi Database/Data warehouse Control Protocol (Stack): 1) SQL commands , 2) Open Network Computing (ONC) Remote Procedure Call (RPC) , 3) Open Cloud Computing Interface for Cloud API Further Standards: 1) Open Carge Point Protocol (OCPP) for Communiction with CMS and Charging Station, 2) Open Smart Charging Protocol 1.0 (for 24h-prediction integration) for Smart Grid and CMS, 3) P2030.5 - Standard for Smart Energy Profile Application Protocol
MTD-SAP: Metadata SAP	Metadata Harvesting Protocol (Stack): 1) OAI-PMH (using XML) / [HTTP/IP] for meta-data harvesting with an available CKAN plug-in, 2) INSPIRE/CSW harvesting with an available CKAN plug-in Service & Metadata Discovery Protocol (Stack): 1) XROAD Message Protocol v4.0 / HTTP, 2) GS1's Object Name Service (ONS) for authoritative metadata and services associated with a given id-key Application Programming Interfaces for Meta-data Access: 1) CKAN API using JSON Implementations, 2) CKAN, Socrata Meta-models: 1) Data Catalog Vocabulary (DCAT) (is an RDF vocabulary), 2) Common Warehouse Metamodel (CWM), 3) DCAT-AP, 4) The Open Graph protocol (more data type) for

	describing web objects (e.g. used by Facebook and google), inspired by Dublin Core, 5) RDF
DX-SAP-Data: Exchange SAP	Data Transfers Protocol Stack: 1) Remote Direct Memory Access protocol over Converged Ethernet (RoCE), 2) FTP or SFTP or others/ WiMAX directed wireless using orthogonal frequency division multiplexing (OFDM), 3) NFS, Network File System - uses remote procedure calls in a sense, 4) Kafka (data & metadata) API
DSD-SAP: Data Sources Data SAP	Standard Messaging Protocol Stack: 1) CoAP /TCP/IP/(Ethernet) - direct device-2-device massaging, optimized for IoT, 2) MQTT /TCP/IP/(Ethernet) - Canonical way of doing message systems, 3) AMQP (Advanced Message Queuing Protocol) P2P and publish & subscribe, 4) Threat/TCP/IP/(Ethernet), 5) IEC 60870-5-104/TCP/IP/(Ethernet), 6) DDS (Data-Distribution Service) for Real-Time Systems, 7) NGSI-LD/HTTP/TCP/IP/(Ethernet) Wireless Messaging Protocol Stack: 1) CoAP or MQTT or AMQP or Threat or IEC 60870-5-104/TCP/IP/GPRS or 3G or 4G - uses standard mobile network, 2) CoAP or MQTT or AMQP or Threat or IEC 60870-5-104/TCP/IP/WiMAX, LTE (optional: OFDM) or UMTS Streaming Data Protocol Stack: 1) H.246/RTP/TLS(SRTP)/IP - for video/streaming data Stream Establishment / Connection Negotiation / Control Stack: 1) SIP or SDP /TCP + TLS/ UDP/ IP/ Ethernet, 2) (S)RTCP/ (S)TCP secure version for connection negotiation, 3) RTSP - for video play pause control, 4) PSIP more for television metadata (but can be used for many kinds of systems)
RWD-SAP: Raw Data SAP	Short Range Wireless Small Device Messaging Protocol Stack: 1) Zigbee or CoAP /UDP/IPv6 + RPL + 6LoWpan/IEEE.802.15.4 Mac & PHY - IoT Protocols for small devices e.g sensors, 2) ZigBee, 3) MQTT-SN - improved version for IoT, 4) MQTT legacy solution, but bigger overhead, 5) Thread or Zwave / IPv6 + RPL + 6LoWpan/IEEE.802.15.4 Mac & PHY - connect and control products at home Wide Range Wireless Small Device Messaging Protocol Stack: 1) LoRaWAN - network protocol intended for wireless battery operated Things in regional, national or global network, 2) NB-IoT, 3) LTE-MTC, 4) EC-GSM-IoT Wired Small Device Messaging Protocol Stack: 1) Modbus, 2) CAN, 3) RS-485 Specific Raw Data Protocol Stack: 1) low energy Bluetooth for control of video signal, 2) OMA LightweightM2M - for coordination of small devices, 2) SSI (Simple Sensor Interface) simple direct access from PC to sensors, 3) LLAP - lightweight local automation protocol Further Standards: 1) DC Charging points: IEC 61851-24, 2) SensorML, 3) NGSI-LD
MGM-SAP: Machine Management SAP	Static Device Management Protocols (Stack): 1) SSH / TCP or UDP - widely used to have a direct connection with a somewhat bigger device/PC/server/machine, 2) Telnet/TCP legacy solution, pre-SSH, 3) TR-069 - originates from the Broadband Forum, 4) SNMP, 5) NETCONF Mobile/Small Device Management Protocols (Stack): 1) Mobile Device Management (MDM) Protocol dedicated mobile device management protocol, 2) OMA Device Management via XML, req+response / WSP (WAP), HTTP, or OBEX / wireline (USB, RS-232) and wireless media (GSM, CDMA, IrDA, or Bluetooth), 3) OMA LightweightM2M – lightweight, to be used mostly within data sources layer, 4) JSR 233: J2EE Mobile Device Management and Monitoring Specification, 5) Open Trust Protocol (OTrP) Network Management Protocols Stack: 1) Simple Network Management Protocol (SNMP) Internet standard protocol for managing IP Network devices, 3) TR-069 - interface often

	used for router configuration
BCN-SAP -Beacon and Near Field SAP	Bilateral/Cluster BCN Protocols (Stack): 1) Hypercat, 2) Physical Web, 3) mDNS, 4) UPnP Unilateral BCN Protocols (Stack): 1) NFC - newer, more data can be transferred, 2) RFID- widely used Bilateral/Cluster BCN Protocols (Stack): 1) Time Synchronized Mesh Protocol (TSMP), 2) OMA LightweightM2M v1.0 for coordination
RtCD-SAP - Routing Coordination and Discovery SAP	Network Layer Protocols : 1) ICMP(v6), 2) IPv4/v6, 3) IPSec, 4) MPLS … Routing Protocols: 1) RIP/RIP-ng, 2) OSPF(v3), 3) BGP(v4), 4) IS-IS ... Other network coordination protocols: 1) Network Time Protocol, 2) DHCP(v6), 3) Neighbor Discovery, 4) ARP, 5) DNS …
ATH-SAP	Authentication / Authorization Protocols: 1) Kerberos, 2) Radius, 3) Diameter - pre-Radius Authentication, 4) PKI Authentication, 5) LDAP, 6) XACML, 7)ACL, 8) OpenID, 9) OAuth

7. Technologies of Relevance for oupPLUS

This section provides a deep dive into the technologies being relevant for oupPLUS.

7.1 Overview of Potential Smart City Technologies

The following aspects are main pillars for a future urban ICT eco-system: (1) IoT Sensors and IoT Communication Protocols, (2) 5G, (3) Public Wi-Fi, (4) Fibre Infrastructure, (5) Cloud/Edge Infrastructure, (6) Open Data, Big Data, (7) Geographic Information Systems, (8) Data Analytics and Artificial Intelligence, (9) City Dashboards, (10) End User Applications and Services and (11) Data Governance and Sovereignty. All of these aspects can be mapped to the layers of the above described reference model and can realize different instances of ICT solutions and platforms in an urban infrastructure. Thereby, all of these technologies can be instantiated and conduct different tasks within a Smart City reference model. The technologies listed in Table 2 offer open interfaces and standards, which make it possible to map them to the capabilities of OUP/oupPLUS and embed them into an urban ICT eco-system via the corresponding open interfaces. The technologies are subject to further development in the ICT research domain.

Table 2: Technologies of Relevance for Future Smart Cities

Technology	Decription
IoT Sensors and IoT Communication Protocols	Devices that can measure aspects such as temperature, humidity, gas levels, and infrared radiation (but not limited to those) and can communicate measured values to an IoT platform are termed as IoT sensors. For the IoT sensors and actuators to function in tandem with the belonging IoT platform (in the backend/cloud), it is necessary that they are able to establish communication channels to the platform, and understand each other's transmitted messages. This is possible when the communication between the various components follows a prior agreed format for self-identification, peer discovery, device management and data transfer among other aspects. Typical protocols from this domain are given by CoAP, MQTT, LoRaWAN, ZigBee, IEEE 802.15.4, NB-IoT, Sigfox and 6LowPAN, to name some examples.
5G	5G is the fifth generation of standards for cellular wireless communication. With the 5G infrastructure in place, the data transfer rates will multiply by about 100 times offering network latencies as low as 1-10ms and 1000 times more capacity, while reducing the mobile data delivery costs by a factor of 10 in comparison to the current 4G networks [7][8][9]. A 5G infrastructure would also support a significantly larger number of concurrent connections, which implies that the same network has the potential to facilitate IoT infrastructures at a large scale suitable for Smart Cities.

Public Wi-Fi	Public Wi-Fi is a service offer, in which the cities offer free Internet access to their citizens and tourists usually at the most important and popular spots in the city. This indirectly helps retain the Wi-Fi users for a longer period of time, which in turn helps the local businesses. Moreover, it also offers a platform for the city to share various tourist information and promote local events & businesses.
Fiber Infrastructure	Optical fibers are the fastest medium of data transmission that offers the highest efficiency and bandwidth. They also support communication over very long distances [11]. In addition to the benefits mentioned so far, the optical fibers are also resistant to electromagnetic interference; so more secured and reliable. They are also much lighter, thinner, flexible and corrosion resistant in comparison to copper wires.
Cloud/Edge	Cloud computing is a paradigm that makes automatic on-demand provisioning of various computing resources such as processing power and storage, without the active direct intervention from a user. With cloud computing the resources are physically placed and maintained within large data centers, while the computing resources are shared as per demand among various users over the Internet. Advantages of cloud computing are manifold; some of them are automatic resource provisioning, easy accessibility of resources, virtually unlimited availability of computing power and storage. Edge computing on the other hand is a distributed computing paradigm where the computation is done at or pushed closer to the data source rather than moving the data to a remote centralized processing unit. Edge computing is highly relevant in the context of IoT and 5G. The benefits of this approach are bandwidth savings, improved response times for orchestration and feedback-based systems.
Open Data/Big Data	According to the European Open Data Portal, *"Open data is data that anyone can access, use and share. Governments, businesses and individuals can use open data to bring about social, economic and environmental benefits."* [12] It also states that Open Data must be licensed and must allow people to transform, combine, share it for any purpose they deem without any binding restrictions, both commercially and non-commercially. The major sources for Open Data are, but not limited to, scientific communities, governments and non-profit organizations. On the site of disadvantages, Open Data might be biased, violate privacy unintentionally, misinterpreted and misused, lead to decisions because of the poor data quality and cause unclear accountability among other possibilities [13]. Oxford defines Big Data as *"extremely large data sets that may be analyzed computationally to reveal patterns, trends, and associations, especially relating to human behavior and interactions."* Technologically speaking Big Data also refers to the processes, technical frameworks and tools involved in the data collection and information analysis from the captured data.
Geographic Information Systems	Geographic Information Systems (GIS) constitute a technology which has been already in use by public administrations for the past decades, in order to manage different types of information with geographic relevance. Especially, GIS systems capture different map structures and manage geographically various objects, for instance properties, sizes of land area etc. There are different relevant formats which capture data and metadata for such GIS systems, with INSPIRE ISO 19115 being the most prominent standard in this area. Examples of successful usages are given by land area management, asset management and tracking, as well as various types of visualizations (e.g. map based COVID-19 dynamics illustrations).
Data Analytics and Artificial Intelligence	Data analytics as the name suggests is the process of cleansing, transforming, examining and visualization of datasets, usually to gather insights that assist in decision making and establish a correlation between the various factors involved. Very often, the integration of data from various sources is a pre-step to data analytics. Artificial intelligence (AI) is a field of computer science, in which machines act upon inputs from their environment by simulating human intelligence, while incrementally learning from the interpretation of the input values. AI can be trained to perform a variety of tasks. Some applications of AI in the scope of IoT are to predict maintenance, automation failures, connectivity issues and intelligent orchestration of tasks in a complex IoT system.
City Dashboards	City dashboards provide the possibility to gain an overall view on certain aspects of a Smart City (area). Typically, city dashboards aggregate data from different sources, including Urban Data Platforms, Open Data portals, GIS systems, IoT platforms and data from commercial data providers (e.g. from mobile network operators). In that sense, city dashboards allow to configure a particular

 doi:10.20944/preprints202012.0064.v1

	set of canvases that enable the aggregated KPI/metrics' monitoring relating to specific areas and aspects such as air quality, traffic congestion, crowd management, energy management, water management and further.
End-User Applications and Services	Typical scenarios that use data efficiently include city dashboards and end-user applications and services. These applications and services can either work autonomously on the basis of predictions drawn from models (as for the regulation of traffic and public lightening), give valuable feedback to decision makers as to the success of their policies, or provide incentives for citizens to change their behavior in a manner, which both benefits them and the society. These end-user applications and services can range from very complex and critical systems involved in energy distribution and retention, over business oriented services as E-Vehicle rental, to simple information applications about the current state of the city, providing information about traffic peak hours, own energy consumption in comparison to other households and suggestions for optimizing the own behavior.
Data Governance and Sovereignty	The topic of Data Governance and Data Sovereignty is a key ingredient in future Smart Cities. This challenge should be approached on technical and organizational level as well. On organizational level different committees/groups should be setup to regularly review data to be released (e.g. in a municipality) and allow or disallow its publication. On the technical level, emerging concepts such as GAIA-X and the International Data Space (IDS) provide methods and technologies to annotate data sets with belonging usage/utilization rights and to automatically allow or disallow access to data based on these pre-configured rules. Thereby, data is automatically validated before its communication or publishing and belonging policies are evaluated, in order to keep control and guarantee data governance and sovereignty.

7.2 *Quality Assurance Technologies and Principles*

As discussed in Section 4, the systematic quality assurance is the key to achieving trustworthy and resilient integrated Smart City infrastructures. This is best achieved by first providing an overview of various available urban ICT solutions and components and secondly providing the means for systematically testing and certifying those solutions/components.

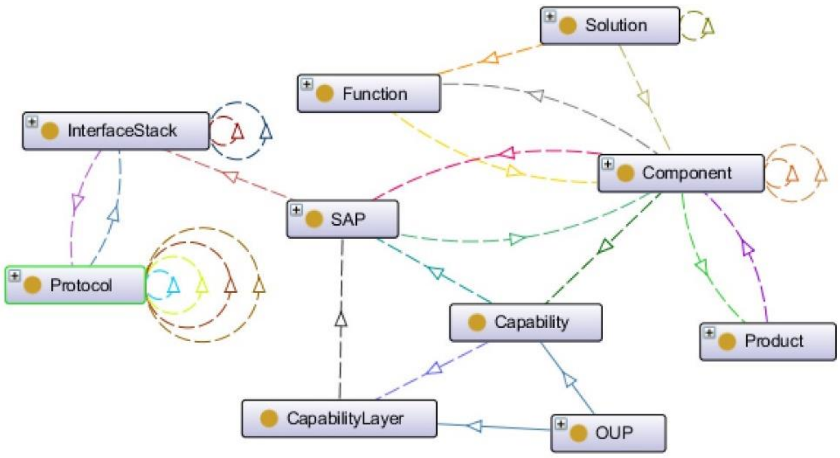

Figure 5: The abstract oupPLUS based Ontological Structures for describing Smart City ICT Components and Solutions

oupPLUS provides a meta-model for the ICT infrastructure in a city, in order to structure the quality assurance for an urban ICT (see Figure 5). It can be used to describe different potential components and solutions by assigning them to different layers/pillar as well as belonging SAPs and concrete interface/protocol stacks as described in Section 6. Furthermore, a component/solution/product should only be accepted (and deployed) when it adheres to the principles defined in the relevant OUP standards, such as the utilization of open interfaces based on open standards. Figure 5 contains an excerpt of an oupPLUS ontology for the purpose of describing Smart City solutions, components and overall ICT eco-systems based on principles of oupPLUS. In Figure 5, we see all artifacts from Figure 4 including the OUP layers, the capability maps for a solution/component, the SAPs from oupPLUS as well as the abstract interface/protocol stacks for communication over an SAP as described in Section 6 and exemplified with concrete instances in Table 1. Hence, Figure 5 provides the basic artifacts which are required in order to start cataloguing and describing urban ICT infrastructures in addition to the illustrations in Figure 6. These illustrations provide on one hand a more elaborated description of the technical aspects (SAPs, interface/protocol stacks, …) whilst at the same time showing the relation to a business perspective including the notion of product and further business views when designing an urban ICT. These extensions and integrational aspects were developed in collaboration with a German Smart City portal for creating a supply/demand business community for Smart City solutions. By that, the oupPLUS meta-model descriptions support the conceptual integration or orchestration of organizational, governmental or business perspectives, which is typically required for a Smart City.

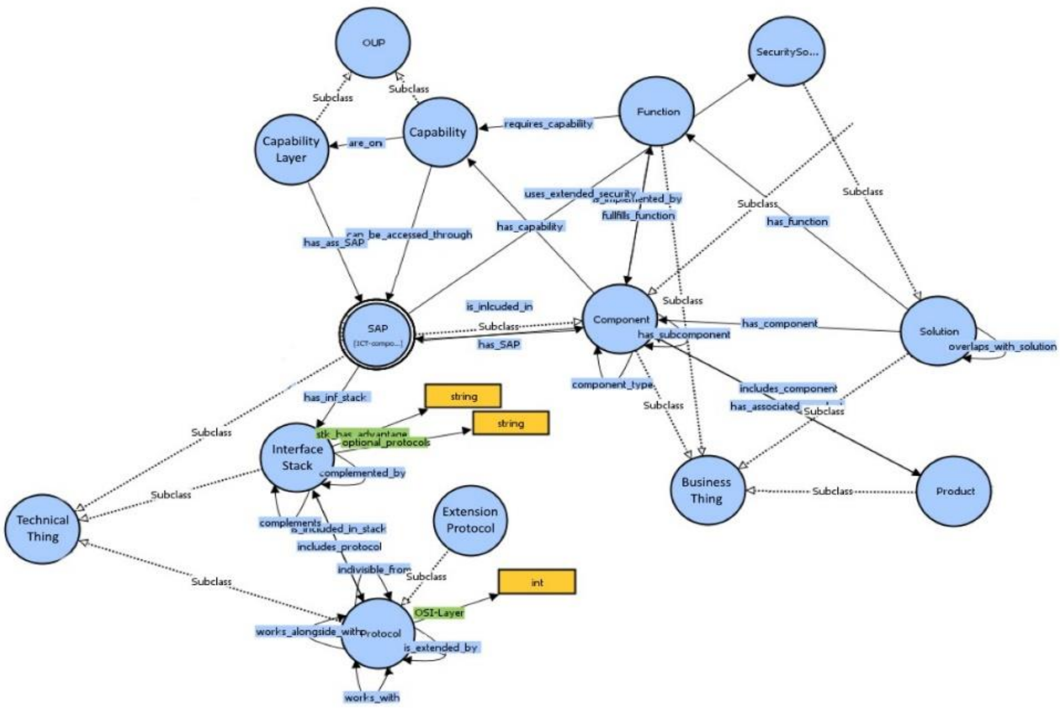

Figure 6: Extending the oupPLUS Ontology by Aspects allowing the Integration in Business Perspective Views on Smart Cities

In order to achieve a complete approach towards the systematic quality assurance and testing of urban ICT, one last ingredient is missing. The oupPLUS based description of an ICT infrastructure typically contains many solutions/components/products mapped to layers/pillars, SAPs and interfaces/protocol stacks. Therefore, systematic tests at the SAPs with regard to the required interfaces and protocol stacks are needed. By that, the conformance (to standards and requirements), interoperability, security, performance and resilience of the components, systems and overall solutions and the particular urban ICT infrastructure as a whole are assured. Table 3 provides examples of available automated test suites, which can be used at the oupPLUS SAPs. The testing

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approaches are to be accompanied by practical and appropriate certification approaches for urban ICT. ICT solutions for Smart Cities should be applied only if the required quality has been validated, in order to guarantee an overall level of resilience and trustworthiness of a Smart City infrastructure.

Table 3: Examples of Available Test Suites that can be applied on the oupPLUS SAPs and further utilized for automated Testing and Certification

Protocol	Test Suite	Type	Platform & Programming Language	Coverage	Provider
SIP	Conformance Test Specification for SIP	Conformance	TTCN-3/Test Specification	RFC3261 - Session Initiation Protocol (SIP)	ETSI
IPv6	IPv6 Ready Logo Program	Conformance / Certification	Test Specification + Test Suite tools	Basic RFC Conformance, Basic Interoperability, IPv6 Core Protocols, IPSec, IKEv2, MIPv6, NEMO, DHCPv6, SIP, IMS UE (Trial) Management(SNMP-MIBs), IKEv1, MIPv6 with IKEv1 MLD	IPv6 Forum
IPv6	IPv6 Test Suites Conformance Test Suites	Conformance	TTCN-3/C++	DHCPv6 (RFC3315, RFC3646, RFC3736), RIPng (RFC2080)	IRISA, France
IPsec	IPv6 Ready Logo Program - phase-2-ipsec	Conformance / Certification	Test Specification + Test Suite tools	IPsec Test Specification (Version 1.11.0), IPsec Interoperability Test Scenario (Version 1.11.0) Phase 2, IPSec Test tools (IPv6PC/TAHI Project), Self-test Tools (IOL INTACT) Phase2, IPsec Conformance (v2.0.0b) Phase2, IPsec Interoperability (v2.0.0b) Basic RFC Conformance, Basic Interoperability	IPv6 Forum
SOAP	SOAP Version 1.2 Specification Assertions and Test Collection	Conformance	Test Specification	SOAP 1.2	W3C
HTTP	Jigsaw A set of HTTP/1.1 features	Conformance	Test tool	HTTP/1.1, Chunk Encoding, TE, TE (bis), Connection Cache-Control, Content-MD5, Retry-After (delay), Retry-After (date), 300 Multiple Choices, 414 Request-URI Too Long, Redirect test page, Basic Authentication test, Digest Authentication test, Content-Location test	W3C
MQTT	IoT Testware MQTT Test Suite	Conformance	Test specifications &	MQTT Version 3.1.1, OASIS Standard, 29 October 2014	Eclipse IoT Testware Project

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			TTCN-3		
CoAP	IoT Testware CoAP Test Suite	Conformance	Test specifications & TTCN-3	RFC7252: The Constrained Application Protocol (CoAP)	Eclipse IoT Testware Project
6LoWPAN	6LoWPAN Test Suite from INRIA	Conformance	Test specifications & TTCN-3	RFC 4944 Transmission of IPv6 over IEEE 802.15.4 RFC 6282 Header compression for 6lowpan	INRIA
ZigBee	Zigbee Testing and Certification	Conformance	not publicly available	not publicly available	TüV Rheinland Germany & SeaSolve Software
LoRaWAN	LoRaWAN® Certification Test Tool (LCTT)	Conformance	not publicly available	LoRa Alliance® European EU 863-870MHz Region End Device Certification Requirements document LoRa Alliance® US + Canada US902-928MHz Region End Device Certification Requirements document …	LoRaWAN Alliance
IEE.802.15.4	SeaSolve IEE 802.15.4	Conformance	not publicly available	not publicly available	SeaSolve Software
LDAP	OpenLDAP Tests	Conformance	Linux, C, *.sh	OpenLDAP Implementation	OpenLDAP.org

8. Towards Reliable Information and Communication Technology for Resilient Smart Cities

This section summarizes our key findings for a viable path towards the establishment of reliable and trustworthy urban ICT for Sustainable Smart Cities across Europe and the globe in the coming decades. We structure the recommendations in four categories (see Table 4) relating to oupPLUS and present calls for action based on the current state of play.

Table 4: oupPLUS based Recommendations for Resilient Smart Cities

Category	Recommendations	oupPLUS layer/pillar
Data Sources	**Recommendation 1:** Increase deployment of sensors **Recommendation 2:** Rely on open source sensor platforms **Recommendation 3**: Deploy municipal sensor networks **Recommendation 4:** Diversify the access technologies at the edge **Recommendation 5:** Place data quality processes close to the data source	0. Field Equipment/Device Capabilities 2. Device Asset Management & Operational Capabilities 8. Privacy and Security Capabilities 10. Network, Systems and Data Management

Network and Connectivity	**Recommendation 6:** Establish special city network backbones (service-oriented network slices) **Recommendation 7:** Secure urban ICT by trusted services to avoid hacker attacks **Recommendation 8:** Establish urban ICT in a redundant manner for more than 99% availability **Recommendation 9:** Utilize state of the art technologies **Recommendation 10:** Be open for new technologies and prepare early for upcoming technologies	1. Communication, Network & Transport Capabilities 8. Privacy and Security Capabilities 10. Network, Systems and Data Management
Solutions	**Recommendation 11:** Provide catalogues of ready-to-go solutions and components **Recommendation 12:** Adopt sufficient automated quality assurance measures for urban ICT	7. Stakeholder Engagement & Collaboration Capabilities 9. Common Services Capabilities
Processes:	**Recommendation 13:** Establish certification schemes for Smart City solutions **Recommendation 14:** Make certification facilities continuously available and affordable in order to enable quick recertification **Recommendation 15:** Urban ICT infrastructure should be managed by agile DevOps like processes, which should also be certified.	7. Stakeholder Engagement & Collaboration Capabilities 8. Privacy and Security Capabilities 9. Common Services Capabilities

9. Summary

This paper summarizes a series of research relating to the systematic development of urban ICT and Smart Cities, which are based on the ongoing development and standardization activities conducted by Fraunhofer FOKUS. The core topic of this paper is given by the fundamental need to develop reliable and trustworthy ICT solutions and infrastructures for Sustainable Smart Cities. Thereby, we started with a review of various related research and development activities including long-term initiatives such as FI-WARE or European projects such as Triangulum and Espresso. Afterwards, we laid the fundamentals for further discussions by defining the terms of Sustainability, Smart Cities and Sustainable Smart Cities according to which we continued developing a set of relevant concepts on reliability and dependability. In order to systematically approach the topic of resilient and trustworthy urban ICT for Sustainable Smart Cities, we introduced the concept of Open Urban Platforms and according reference architecture models. We highlighted with oupPLUS the quality assurance requirements on urban ICT, which are central for high quality reliable ICT infrastructures as a backbone for Smart City processes. oupPLUS is discussed in detail towards the establishment of sophisticated quality assurance and certification processes for reliable and

 doi:10.20944/preprints202012.0064.v1

trustworthy urban ICT. Based on our practical experiences, we provided selected examples for methods and tools (e.g. test suites) and discuss in relation to the reference architecture current and upcoming technologies, which are important for Smart Cities. Based on our lessons learned in numerous practical Smart City projects, we provide concrete recommendations for achieving reliable and trustworthy urban ICT and Sustainable Smart Cities within the scope of the oupPLUS Open Urban Platform.

Author Contributions:

Dr. Nikolay Tcholtchev has made solid contributions during the past years to all related fields discussed in the current publication, especially to the areas and standardization activities for Open Urban Platforms and ICT reference architectures for Smart Cities. Furthermore, he is an expert in the domain of quality assurance and testing and hence his main contributions are related to Section 6, Section 7 as well as to the recommendations for reliable urban ICT in Section 8. Beyond that, Nikolay Tcholtchev contributed to shaping all the other sections of the paper.

Prof. Dr.-Ing. Ina Schieferdecker contributed to this research during her time as team leader and institute director at the Fraunhofer Institute for Open Communication Systems in Berlin. She was intensively involved in the discussion and standardization activities relating to the topics of Open Urban Platforms and engineering support for Smart Cities. In this regard, her main contributions are reflected in Section 5, Section 7 and especially in the introduction and definitions' parts of this paper, i.e. Section 1 and Section 3.

Conflicts of Interest: The authors declare no conflict of interest.

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