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Ecosystems of Social Digital Twins for future IoT network

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People involved in the addressed research

Core team

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- Antonio Iera — Università della Calabria
- Giacomo Morabito — Università di Catania

Major contributors

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- Olga Chukhno — A-WEAR
- Nadia Chukhno — A-WEAR
- Claudia Campolo — Università Mediterranea di Reggio Calabria
- Giacomo Genovese — Università Mediterranea di Reggio Calabria
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- Giuseppe Milotta — Università di Catania
- Antonella Molinaro — Università Mediterranea di Reggio Calabria
- Michele Nitti — Università di Cagliari
- Sara Pizzi — Università Mediterranea di Reggio Calabria
- Salvatore Quattropani — CNIT

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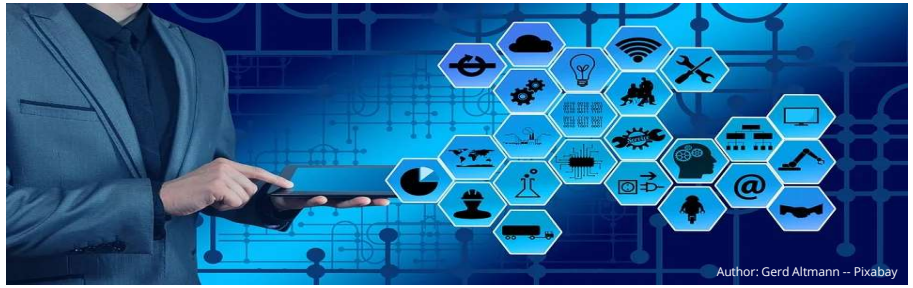
5G-IoT landscape



- Population of massively connected devices, different from the current one
- The lion's share taken by sensors & actuators and by everyday augmented objects typical of the Internet of Things (IoT)
- Virtualized and programmable network functions and resources
- Delivery of new and increasingly sophisticated services to heterogeneous groups of (mobile) devices

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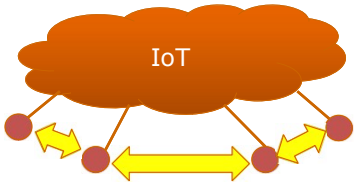
Issues related to the IoT "structure" in 5G

… a «side effect» in current 5G-IoT

What IoT was supposed to be:

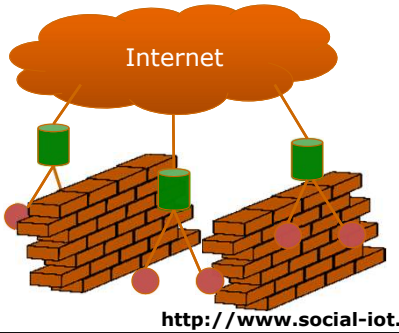
"A worldwide network of interconnected objects, uniquely addressable based on standard communication protocols"

(2015 by Drew A Hendricks)



What it currently is:

"A bunch of platforms in which objects are not uniquely addressable and their interaction is possibly based on the use of proprietary semantics and protocols"



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Causes and effects

Causes	Effects
▪ Slow standardization process ▪ IT companies could not wait for the end of the "*war of IoT protocols*" ▪ Well established business models ▪ Simplicity granted by a centralized database	▪ Difficult/impossible interactions between platforms ▪ Lack of global resource directory & discovery ▪ Heterogeneous semantics ▪ Difficult to distinguish infrastructure from service provider ▪ Traditional interaction models only

How to contrast this risky trend??

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Enabling paradigms

we can resort to the joint adoption of three pillars of modern service & network solutions for 5G-IoT

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Enabling paradigms

network softwarization (SDN)

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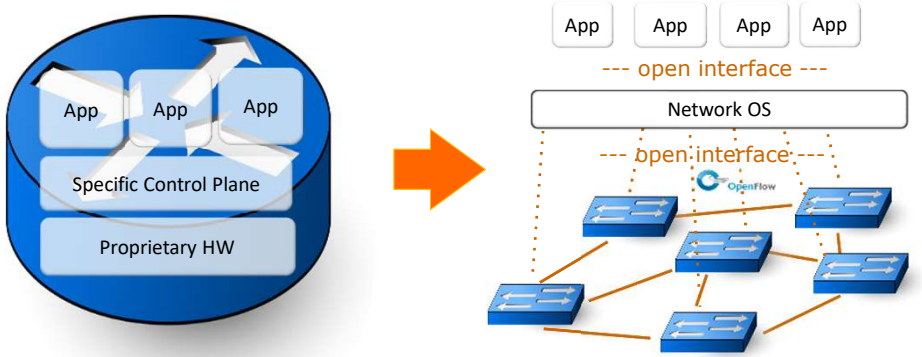
First Pillar: Network Softwarization

- SDN network architecture built upon 4 basic principles:
  - The control and data planes are decoupled.
  - Forwarding decisions are flow-based, instead of destination-based.
  - Control logic is moved to the SDN controller (NOS)
  - The network is programmable through software applications



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Enabling paradigms

network softwarization (SDN) + SIoT "social networks of devices"

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Second Pillar: The Social IoT paradigm

a novel paradigm of "social network of intelligent objects", based on the notion of social relationships among objects[a,b]

What?

- Autonomous establishment of social ties create a social network of devices
- Communication end-points identified in terms of social distance
- Device trustworthiness computed by exploiting the view of the social network.

Why?

- Give the IoT a structure that can be shaped as required to guarantee network navigability so as that service discovery can be performed effectively while guaranteeing scalability.
- Create a level of trustworthiness which could be used to leverage the level of interaction between things that are "friends".

[a] L. Atzori, A. Iera, G. Morabito, "SIoT: Giving a Social Structure to the Internet of Things", IEEE Communications Letters, 15/11, 2011.
[b] L. Atzori, A. Iera, G. Morabito, M. Nitti, " The Social Internet of Things (SIoT) – When social networks meet the Internet of Things: Concept, architecture and network characterization ", Computer Networks, Volume 56, Issue 16, 14 Nov. 2012, Elsevier.

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Enabling paradigms

network softwarization (SDN) + paradigm of "social networks of devices" + Virtualization of physical devices: Digital Twins

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Third Pillar: Digital Twins in the 5G IoT ecosystem

- In many emerging 5G Internet of Things (IoT) deployments, devices and objects associated to digital counterparts (twins)

Objective

- augmenting physical object's capabilities
- acting on its behalf when interacting with other devices
- exposing the resources offered by the device to third-party applications that can access them without directly querying the physical devices

Digital Twins as a way to bridge the physical world with the digital one and favor the deployment of multi-tenants solutions

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Third Pillar: Digital Twins in the 5G IoT ecosystem

- Changing terminology over time, but basic DT concept quite stable since its introduction in year 2002
- The digital footprint originally hosted only in the remote Cloud.
- In more recent approaches, the DT concept coupled with Edge Computing

Advantages

- Edge computing localizes processing resources closer to end-devices
- Data do not cross the network to reach the cloud
  → reduction of network load and the data latency.

Faster response times, improved user satisfaction, and benefits also for network operators and cloud providers.

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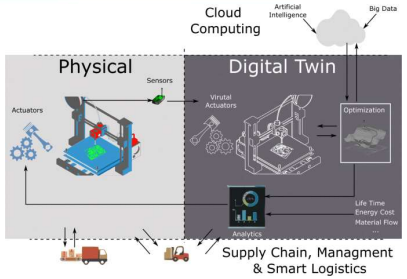
Digital Twins in 5G IoT ecosystems



Source: https://link.springer.com/article/10.1007/s00170-021-06649-8

- DTs in Industry 4.0:
  - optimize processes and products and provide information on the performance and health of a production machinery for predictive maintenance.
- From single asset digital twin to virtual plant replication:
  - companies are starting to link many Digital Twins together, to create virtual models of entire factories, product lifecycles, supply chains, ports and city.

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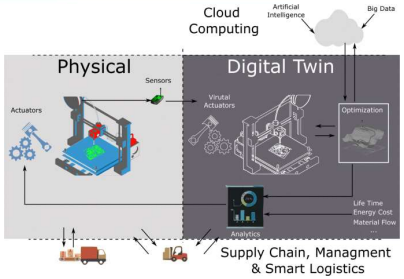
Digital Twins in 5G IoT ecosystems



Source: https://link.springer.com/article/10.1007/s00170-021-06649-8

➢ Building digital twin for personalized medicine:
- to build representations of biological processes and body systems that are affected by viral infection.
- to be integrated with clinical data (maybe taken from body area networks)
- to be used to derive predictions about diagnosis, prognosis, and efficacy and optimization of therapeutic interventions. (N. Cary/Science)

➢ DTs in Industry 4.0:
- optimize processes and products and provide information on the performance and health of a production machinery for predictive maintenance.

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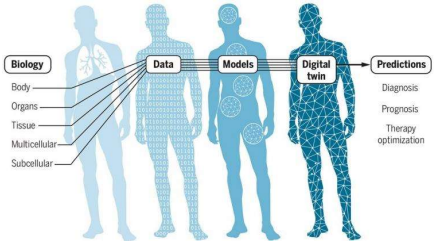
- companies are starting to link many Digital Twins together, to create virtual models of entire factories, product lifecycles, supply chains, ports and city.



https://tectales.com/bio-tech-it/digital-twins-for-more-personalized-medicine.html

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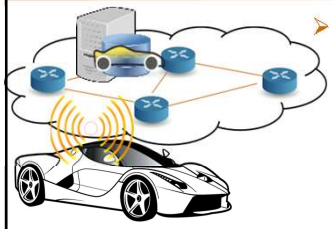
Digital Twins in 5G IoT ecosystems



➢ 5G·V2X Use Case [1]. Each vehicle has a Twin in the MEC facilities, the Virtual Vehicle (VV), which:
- Adds additional functionalities and processing/storage capabilities to the V2X Applications at the VUE.
- is synchronized with the physical vehicle and works on behalf of it.
- Data aggregated over multiple VVs for a more accurate and augmented situational awareness of the road users.

[1] C. Campolo, et al., "MEC Support for 5G-V2X Use Cases through Docker Containers", 2019 IEEE WCNC Conference

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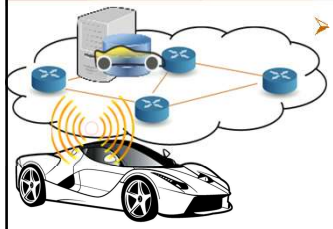
Digital Twins in 5G IoT ecosystems



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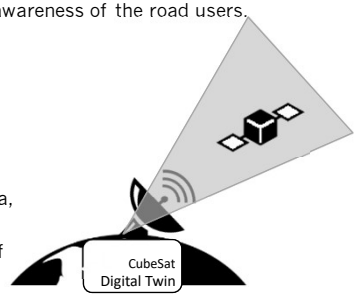
- 5G-Internet of Space Things [2]. NanoSatellite/CubeSat Virtualization through Digital Twins for:
  - Flexible management and orchestration of CubeSat constellations and continuous monitoring
  - Continuous sensing: continuous access to satellite data, not only during its stay under the control of the GS
  - Augmented data fruition: federation of constellations of CubeSats belonging to different Tenants



[1] C. Campolo, et al., "MEC Support for 5G-V2X Use Cases through Docker Containers", 2019 IEEE WCNC Conference
[2] G Araniti, et al., " Opportunistic Federation of CubeSat Constellations: a Game-Changing Paradigm Enabling Enhanced IoT Services in the Sky", IEEE Internet of Things Journal, 2021

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First goal: achieving global system interoperability

Breaking down inter-system walls

- Global interoperability among heterogeneous IoT platforms achieved through end-device digital counterparts connected via social ties (***SDT***, ***Social Digital Twins***).

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Second goal: a new NTW primitive leveraging SDTs

Sociocast

- A ***Social DT- based*** networking primitive to support group communications among physical devices/systems that span several heterogeneous platforms.

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Social issues related with Digital Twins

- Fujitsu Limited and Carnegie Mellon University announced collaborative research projects focused on the development of "Social Digital Twin" technology.[*]

Objective:

- "*Digitally reproducing relationships and connections between people, goods, the economy and society*"

What for?:

- digital twins as simulation, prediction and decision making environment in which to *solve diverse and complex social issues*.

[*] https://www.fujitsu.com/global/about/resources/news/press-releases/2022/0208-01.html

Social issues related with Digital Twins

- NTT laboratories are conducting research and development of Digital Twin Computing (DTC) to achieve new digital societies that fuse the real and virtual. [*]

Objective:

- In contrast to conventional digital twins that have been developed for objects, DTC also focuses on *digital twins of humans*, used in broader social context rather than just as a solution to a specific problem .

What for?

- Social issues with DTC entail ensuring human activities are not hindered in either the real or virtual or discovering such hindrances in advance.

[*] NTT Digital Twin Computing Research Center- https://www.rd.ntt/e/dtc/

Social issues related with Digital Twins

- A recent research [*] has also explored how so called Societal Twins might be developed, validated and used to support real world decision making.

Objective:

- develop societal twins that simulate the decisions, behaviors and interactions of individuals that make up our *social systems*

What for?:

- "*to model the general behavior of a population and its interactions with physical infrastructure over a spatial-temporal scale*"

[*] Towards the Development of Societal Twins , Dan Birks , Alison Heppenstall and Nick Malleson, 24th European Conference on Artificial Intelligence - ECAI 2020

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Our perspective of Social Digital Twins

The cited researches focus digital twins that are "social" because they aim at representing people social interactions and social systems.

Our (different) Idea of Social Digital Twins:

- Digital Twins of physical objects/systems establishing social-like relationships with each other
- Relationships carried over into digital twins, that keep track of them
- Info used by a SDT for socially-based discovery of SDTs (maybe to receive useful additional data to enhance the SDT's predictive models)
- Increased SDT's ability to adapt the behavior of the represented device/complex system to external conditions and user needs

...some examples

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Sample use cases:
Adapting smart environments to specific situations

- The SDT of a complex infrastructure deployed in a smart city area monitors and configures the physical twin based on gathered data from physical components.
- The SDTs of the cars become "friends" with each other and friends of the SDT of the city's infrastructure by coming into contact and exchanging data repeatedly

Source: https://www.ai4business.it/news/

- As they move, they interact with different objects belonging to different infrastructures managed by different owners
- The SDT of the infrastructure can discover, query and receive data (and best-practice configurations) from different smart city infrastructures that are "friend" to the cars that interact with them
  - to adapt the behavior of the physical counterpart to particular situations
  - to gather data from unknown infrastructures for enhanced estimates

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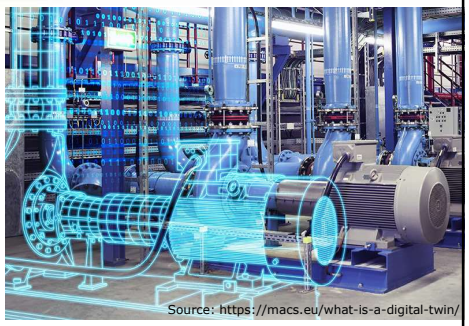
Sample use cases:
Exchange of best-practices in Industry 4.0

- A SDT virtually represents an industrial machine or system, connected to it throughout its life cycle to digitally emulate its behavior, analyze performance and, if necessary, send reconfiguration commands.
- Also workers may have a SDT associated (body area network for health/stress monitoring at work) for health/safety surveillance at work).
- Through established social relations between workers and machinery the SDTs of different plants can
  - discover and exchange best practices with similar machines for quick optimal machine/system reconfigurations (adapt to worker behavior)
  - cooperate and learn from each other for problem solving, collectively achieving production goals
  - develop an system performance management infrastructure for sharing data and analytics to support asset and operations management.



Source: https://macs.eu/what-is-a-digital-twin/

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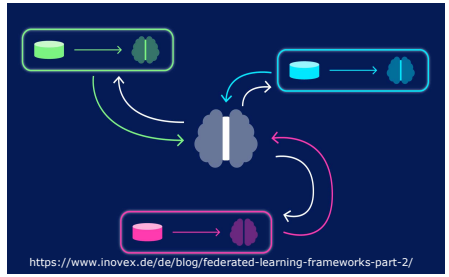
Sample use cases:
Socially-Driven Distributed Learning

- DTs as descriptors of (even complex) computation/caching/learning devices within the network.
- In Distributed Learning there is a need to select the devices that participate in the learning process



https://www.inovex.de/de/blog/federated-learning-frameworks-part-2/

- For example, in Federated Learning the orchestrating server could discover friend devices as learning partners by browsing the social graph linking their Social Digital Twins
- Effect: creation of groups of reliable learners by applying social discovery and social trustworthiness techniques

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- **designing global interoperability via an ecosystem of Social Digital Twins**

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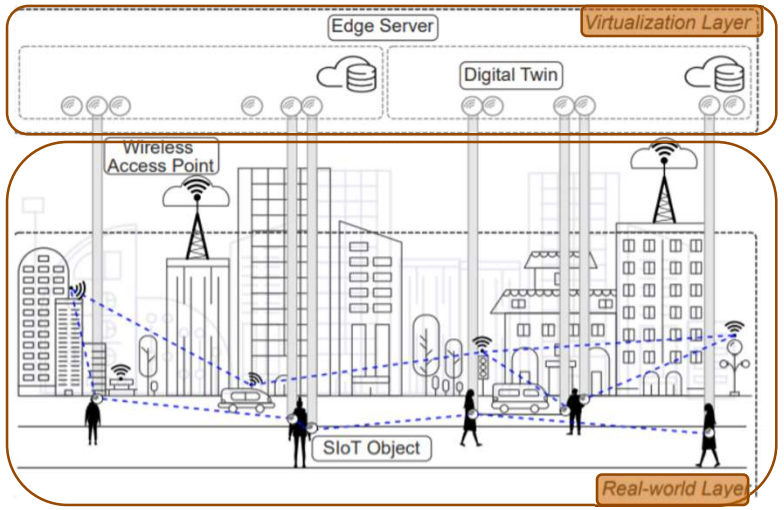
The reference ecosystem of Social Digital Twins



Authors: N. Chukhno, O. Chukhno

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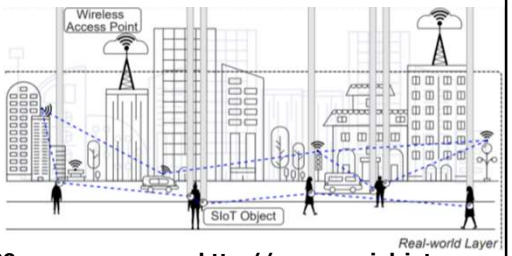
The reference ecosystem of Social Digital Twins

- The **real-world layer** represents the physical world that accommodates IoT objects interconnected with each other and to other entities through connectivity facilities.
- Social relationships among objects are assumed, which are set up according to the SIoT paradigm, such as:
  - ✓ Co-Location Object Relationship (C-LOR) established among objects located in the same place.
  - ✓ Ownership Object Relationship (OOR) specifying connections among objects that belong to the same owner.
  - ✓ Parental Object Relationship (POR) defined among objects belonging to the same production batch.
  - ✓ Social Object Relationships (SOR) is established due to contact of users/devices.



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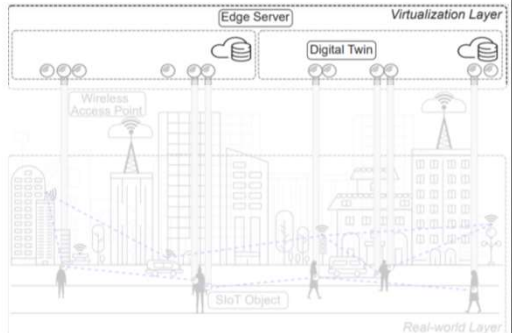
The reference ecosystem of Social Digital Twins

- The virtualization layer is responsible for hosting the digital counterparts of physical devices, i.e., the SDTs.
- The latter offers the typical functionalities a digital counterpart provides:
  - ✓ *caching* and *aggregation* of the raw data transmitted by the IoT device before IoT applications process it.
  - ✓ algorithms for *reasoning* over data
  - ✓ mechanism for behavior *prediction*
  - ✓ in addition, the proposed SDT stores (i) **metadata** describing the device type and (ii) a dynamic list of **established social relationships** with other SDTs.



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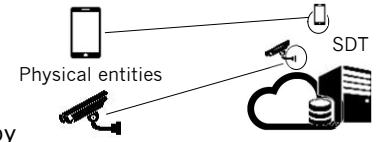
Social Digital Twins at the Network Edge

- A SDT can be deployed and runs in a (Edge) Server
- SDTs inherit the social-like relationships *autonomously* created by the twin physical devices
- Different types of relationships can be stored and dynamically maintained within the SDT
- An example in the literature are SVEs [*] equipped by Friend Tables



Friend table example [*]

Entity ID	Metadata	Relationship type	SDT locator	MS server locator
ID_A	logistics	CWOR	151.70.25.10	151.70.24.1
ID_E	sport	CGLCOR	130.40.0.56	178.30.29.1
ID_D	infotainment	POR	130.40.0.56	178.30.29.1

- New relationships can be always defined and the logic is represented in the data structures and algorithms of the Social Digital Twin itself

[*] L. Atzori, C. Campolo, B. Da, R. Girau, A. Iera, G. Morabito, S. Quattropani, "Enhancing Identifier/Locator Splitting through Social Internet of Things", IEEE IoT Journal, 2018. doi: 10.1109/JIOT.2018.2877756

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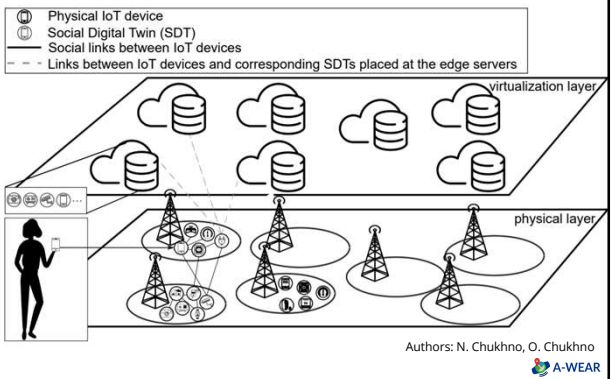
Dynamic placement of digital twins (DTs) with social capabilities at the Edge

Goal

Finding optimal placement of Social Digital Twins at the Edge



Authors: N. Chukhno, O. Chukhno

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Chukhno, O., Chukhno, N., Araniti, G., Campolo, C., Iera, A., & Molinaro, A. (2020). Optimal placement of social digital twins in edge iot networks. Sensors, 20(21), 6181.

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Where to place SDTs?

Authors: N. Chuchkno, O. Chuchkno

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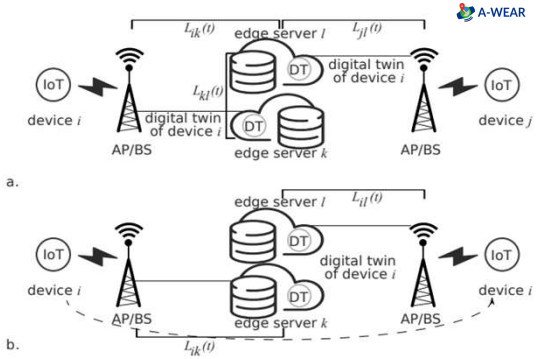
SDTs have to be optimally placed

… and periodically

SDTs have to be optimally migrated after Physical Twin Device movements



The dynamic optimal placement of SDTs has to account for :
types of IoT devices, social features, mobility patterns, and limited computing resources of edge servers.

[*] Olga Chukhno, et al., " Optimal Placement of Social Digital Twins in Edge IoT Networks Services in the *Sky*", Sensors 2020; doi:10.3390/s0010000

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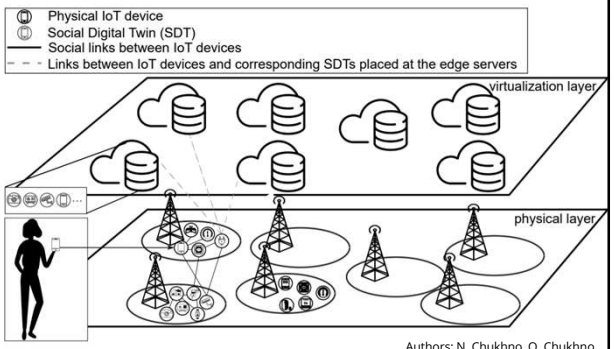
Dynamic placement of digital twins (DTs) with social capabilities at the Edge

Strategy

minimize the total cost of digital twins placement taking into account:

- the average latency of connections between physical devices and their digital twins;
- the average latency between such placed digital twins of physical devices which have friend relationships/connections on the basis of the SIoT.



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Metrics of interest

Authors: N. Chuchkno, O. Chuchkno

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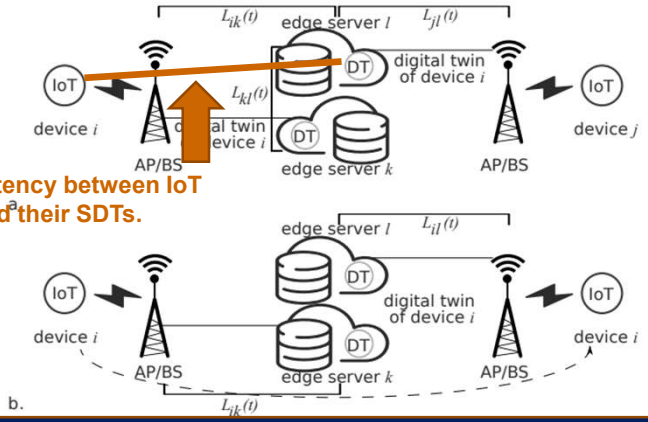

Average latency between IoT devices and their SDTs.

A lower latency among Physical and Digital devices has the straightforward benefit of reducing the travel time of sensed data towards the SDT and of reconfiguration commands towards the Physical Device

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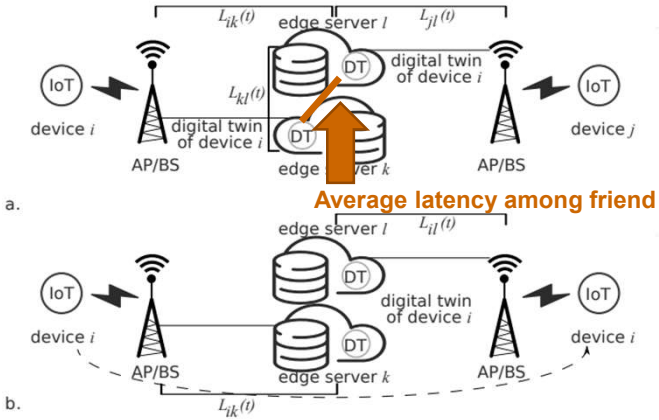

Average latency among friend SDTs.

A lower latency among SDTs has a twofold benefit: (i) the pressure on the network is low, when such SDTs exchange data, and (ii) quick interactions and SDT discovery are ensured.

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Metrics of interest

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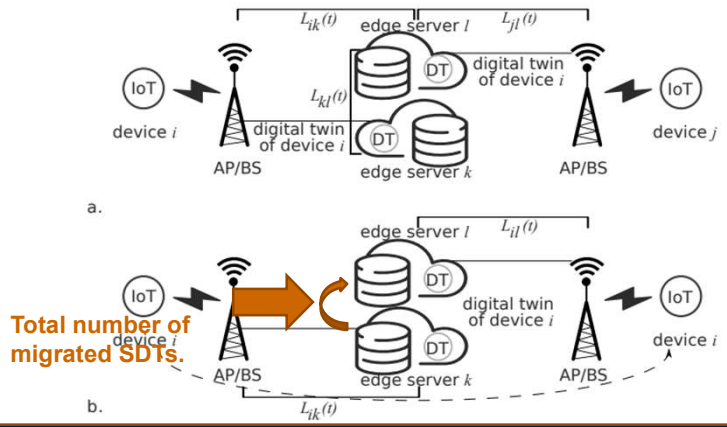

Total number of migrated SDTs.

A lower number of SDTs migration has an additional benefit: a lower amount of data associated to the migration process needs to be exchanged from the source to the target edge server.

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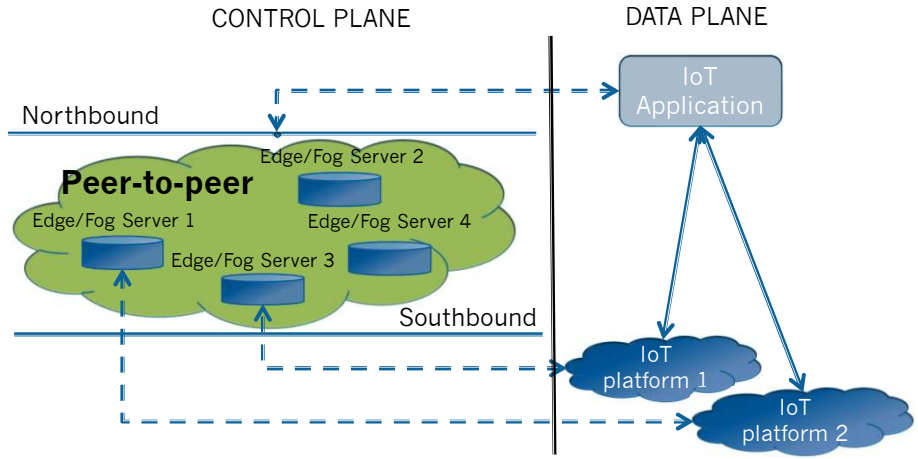
Overcoming inter-platform barriers in 5G-IoT systems populated by SDTs



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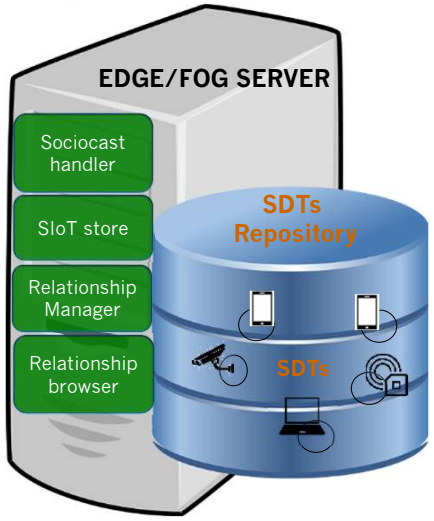
Edge Server components



- The **SDT repository** stores the SDTs
- The **Relationships manager functionality** is responsible of the lifecycle of social relationships established between SDTs
- The **Relationship browser functionality** is used by applications (as well as the sociocast) to navigate the SIoT
- The **SIoT store** is a distributed market place for SIoT applications
- The **sociocast component** supports new communication configurations
  - Beyond unicast, broadcast, multicast, anycast, etc...

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- **… a step forward: designing a new network primitive for group communications based on Social Digital Twins**

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Issues related to data casting in 5G-IoT

the user/device will increasingly act as a *PROSUMER*

Consequence:

proliferation of unicast, broadcast and multicast traffic flows originating from heterogeneous access segments (fed into the network by highly mobile devices)

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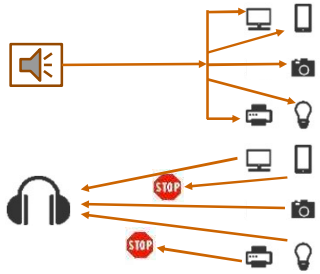
Key players requirements

In environments characterized by highly dynamic & distributed communities



What users want is:

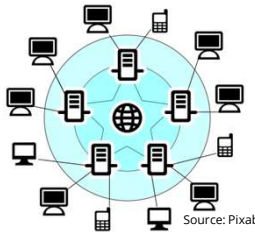
(i) generating content for groups of devices and delivering it in a highly flexible manner;

(ii) receiving only desired traffic from reliable devices, to face the risks of circulation of fake and harmful contents.

What network operators want is:

(i) Keep the network load under control to guarantee committed performance to users

(ii) Easily handle traffic congestion issues



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Are current network primitives ready?

- Multiple unicast links are not an option (too many devices in 5G-IoT)
- Current multicast and broadcast network primitives are likely inadequate:
  - Multicast: underutilized
  - Broadcast: a "nightmare" for network operators due to associated risks of network overload
  - Geocast: too restrictive

As a consequence…

- Design a new network primitive for group communications to:
  - manage plenty of H2H, H2M, and M2M data exchanges
  - support group communications in a flexible, reliable, and quickly (re)configurable way

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Previous approaches

Social ties among devices already used to improve traditional communications paradigms at a middleware, application or cross- layer.

- forward data by limiting the number of relays until destination in multi-hop wireless (*opportunistic* and *delay-tolerant*) networks.
- identify the best data carriers through predictions based on social interactions (*SocialCast*, a routing framework for publish-subscribe).
- implement a *social anycast* communication service in DTN.
- implement video content sharing in Social-aware video multiCast (SoCast) systems to stimulate cooperation among mobile clients.

Idea: to leverage the "social network of Digital Twins" paradigm at the network layer

L. Atzori, A. Iera, G. Morabito (2019), "Sociocast: A New Network Primitive for IoT", IEEE Communications Magazine, June 2019, Vol. 57, n. 6, Digital Object Identifier: 10.1109/MCOM.2019.1800917

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Why we need a "socio"-cast primitive?

The need for a tool to support traditional IP multicast.

- a primitive used by network operators to filter the set of nodes that can join a certain multicast group, based on their position in the social graph.

The need for a dynamic & selective firewall.

- The filtering of the entities that can send it data can leverage:
  - trustworthiness control policies offered by a social network of devices (like in human social networks)
  - the reciprocal position in the social network

The need for higher flexibility in data casting.

- Introduce a network primitive that can make use of data structures, defined in the control plane at the network layer, containing basic metadata for device description.

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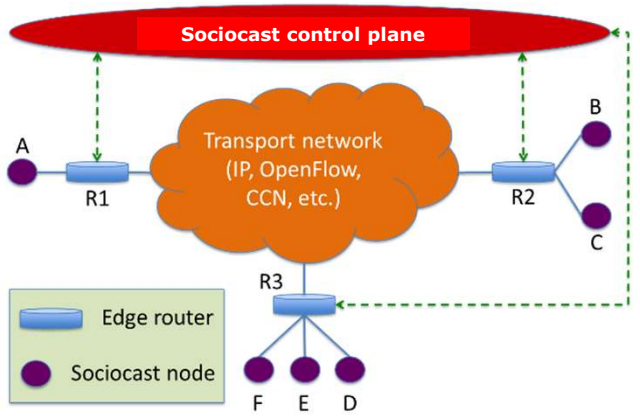
The framework supporting the Sociocast primitive



Early stage of introduction of Sociocast: a new network control plane functionality coupled with existing transport networks.

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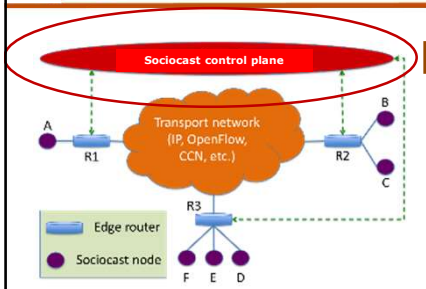
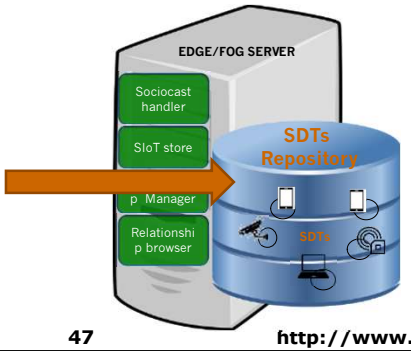
The Sociocast control plane



The Sociocast control plane must implement a set of control plane functionalities relying on a distributed hardware/software infrastructure.

Major components of the Sociocast control plane are the SDT repositories



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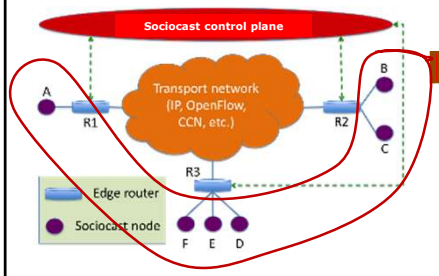
The Sociocast nodes



Sociocast nodes exploit the new network primitive to deliver packets to a set of destinations on the basis of their mutual position in the Sociocast social graph.

The *Social Digital Twin* (STD) , with its "*Friends Table*", stored in the Repository is the digital counterpart of each IoT node

Friend table example

Entity ID	Metadata	Relationship type	SDT locator	MS server locator
ID_A	logistics	CWOR	151.70.25.10	151.70.24.1
ID_E	sport	CGLCOR	130.40.0.56	178.30.29.1
ID_D	infotainment	POR	130.40.0.56	178.30.29.1

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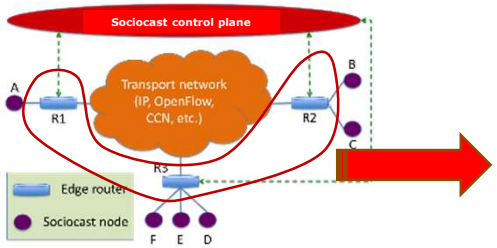
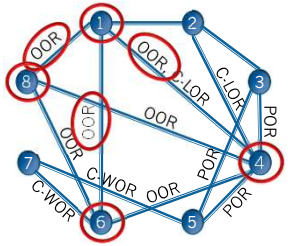
The Sociocast Edge routers



Edge routers are a key component that must intercept incoming packets with certain characteristics, interpret them, interact with the Sociocast control plane, and execute corresponding commands

- *Sociocast* allows to select:
  - The destinations of a packet based on the position of their SDTs in the social network

Sample case: eHealth monitoring systems



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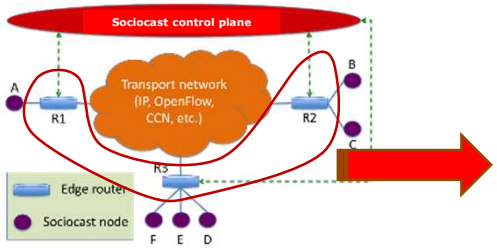
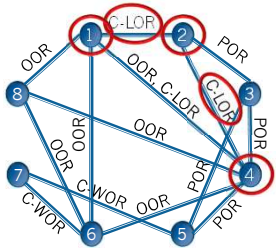
The Sociocast Edge routers



Edge routers are a key component that must intercept incoming packets with certain characteristics, interpret them, interact with the Sociocast control plane, and execute corresponding commands

- *Sociocast* allows to select:
  - The nodes allowed to transmit packets to a certain node based on the positions of their SDTs in the social network

Sample case: travel assistance in I.T.S.



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❑ Implementation issues

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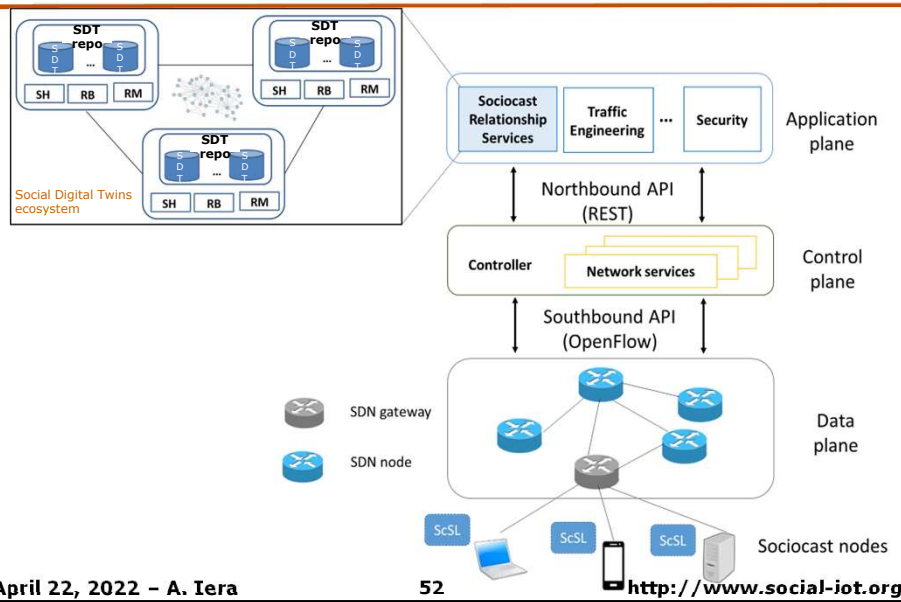
Sociocast support in SDN networks



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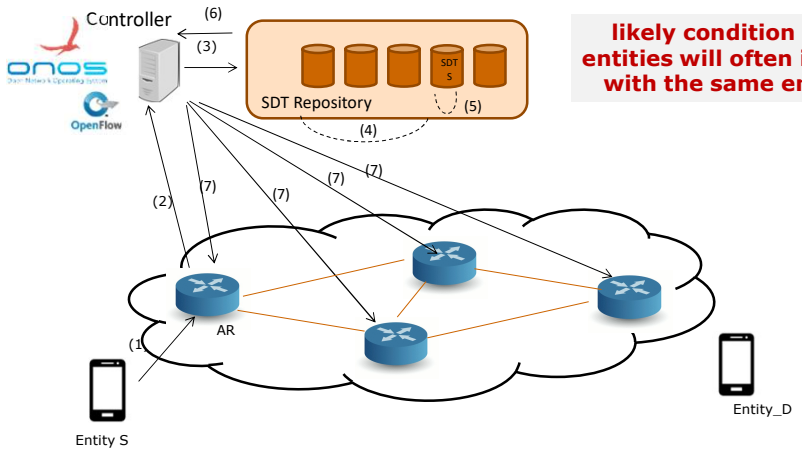
Destination discovery

Case 1. The destination entity is found among the friends of the source entity, stored in the FT



likely condition since entities will often interact with the same entities

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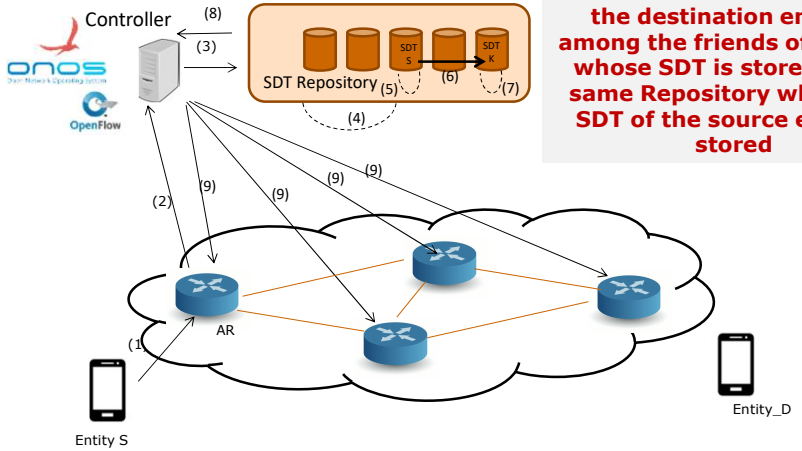
Destination discovery

Case 2. The destination entity is found among the friends of a friend whose SDT is stored in the same SDT Repository



the destination entity is among the friends of a friend whose SDT is stored in the same Repository where the SDT of the source entity is stored

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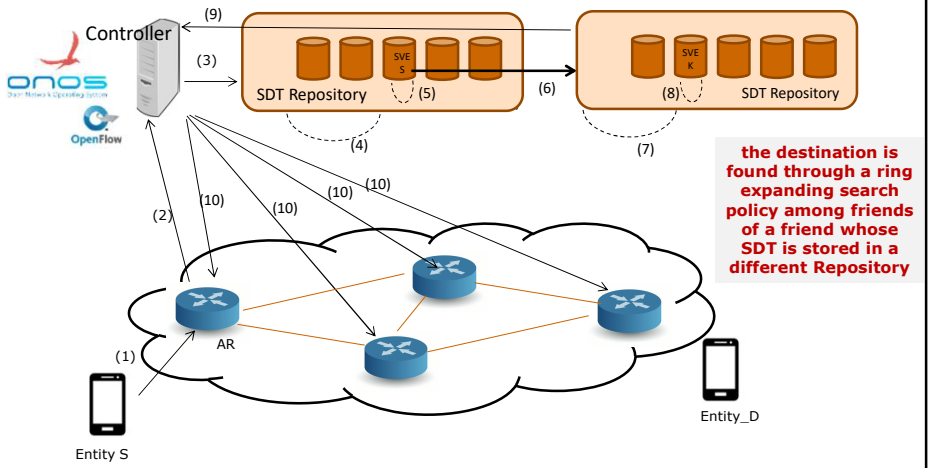
Destination discovery

Case 3. The destination entity is found among the friends of a friend whose SDT is stored in different SDT Repositories



the destination is found through a ring expanding search policy among friends of a friend whose SDT is stored in a different Repository

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Sociocast in action: sociocast-based push service

Packet header relevant fields:
Metadata = 0000
Relation filter = C-LOR = 0001
Feature = Group Creation = 0000
Radius = 2 hops = 0010
0000000100000001 --> 257 (UDP Port)

- The first SD-GW encountered by the packet sends it to the Controller
- The Controller queries the SIoT (the Relationships browser)
- The SIoT replies with a set of destinations
- The Controller sets the forwarding rules in all relevant network elements
- All other packets belonging to the same flow will be forwarded right away

L. Atzori, C. Campolo, A. Iera, G. Milotta, G. Morabito, S. Quattropani, Sociocast: Design, implementation and experimentation of a new communication method for the Future Internet, *World Forum on IoT, WF-IoT 2019*.

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Sociocast in action: publish-subscribe

Packet header relevant fields:
Metadata = 0000
Relation filter = OOR = 0001
Feature = Publish-subscribe = 0001
Radius = 1 hop = 0001
0000000100010001 --> 273 (UDP Port)

- The first SD-GW encountered by the packet sends it to the Controller
- The Controller queries the SIoT (the Relationships browser)
- The SIoT replies with a set of possible sources
- The Controller sets the forwarding rules in all relevant network elements
- Packets published by the sources are forwarded to the node of interest

L. Atzori, C. Campolo, A. Iera, G. Milotta, G. Morabito, S. Quattropani, Sociocast: Design, implementation and experimentation of a new communication method for the Future Internet, *World Forum on IoT, WF-IoT 2019*.

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Open research issues

- *Relationship Manager:*
  - Need for solutions able to find relevant relationships in short time intervals (reasonable computing effort)
- *Placement of Social Digital Twins:*
  - Performance improves if SDTs that establish relationships and interact with each other always run in the best chosen Repository → Optimization
- *Data plane:*
  - Need for a data plane enabling data transfer according to Sociocast primitive. → A non-disruptive transition from existing protocols is preferable.
- *Sociocast programming:*
  - Need for suitable socket APIs (Application Programming Interfaces) with relevant socket options to enable hosts to join Sociocast groups
- *Energy cost:*
  - Devices need to run additional operations → Energy consumption → Optimize the process
- *Sustainability*
  - Identify viable business models
- *Performance analysis:*
  - Need for proving performance of SDT communications against changes in network topologies, user mobility profiles, social graph.
- *Security & confidentiality:*
  - to assure that exchange of information relevant to SDT is secure and controllable by the device's owner