Towards the Internets of the Future

Katia Obraczka

Computer Engineering

UC Santa Cruz

http://www.soe.ucsc.edu/~katia

http://inrg.cse.ucsc.edu

katia@soe.ucsc.edu

Inter-Networking Research Group

About me

- UC Santa Cruz Baskin School of Engineering
- Department of Computer Engineering
- Professor and Graduate Director
- @ UCSC since January 2001.
- 1995-2000
  - Research Scientist at USC's Information Sciences Institute (ISI)
  - Research Faculty at USC's Computer Science Department.

About me

- PhD, Computer Science Department, University of Southern California (USC)
- MSc, Computer Science, USC
- MSc, COPPE-Sistemas
  - Faculty, Dept. de Informatica, UERJ
  - Engineer, EMBRATEL
- BS, Engenharia Eletronica, UFRJ

My research

- Computer networks
- My research lab:
  - Internetworking Research Group (i-NRG)
  - https://inrg.soe.ucsc.edu

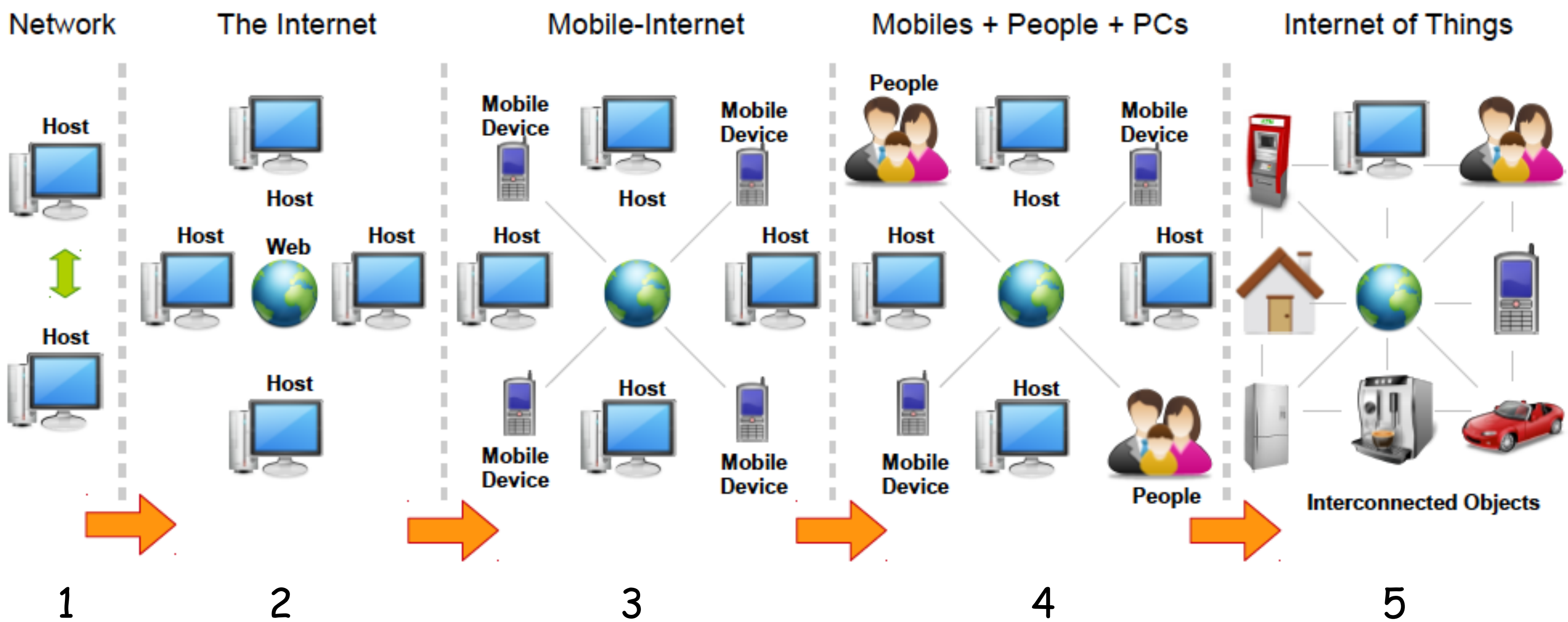
Research at iNRG (http://inrg.soe.ucsc.edu)

- Motivated by vision of future internets.
- Design, develop, evaluate, deploy protocols and services targeting future internets.

Internet evolution

Internet evolution

Perera et al., *Context-Aware Computing for the Internet of Things: A Survey*



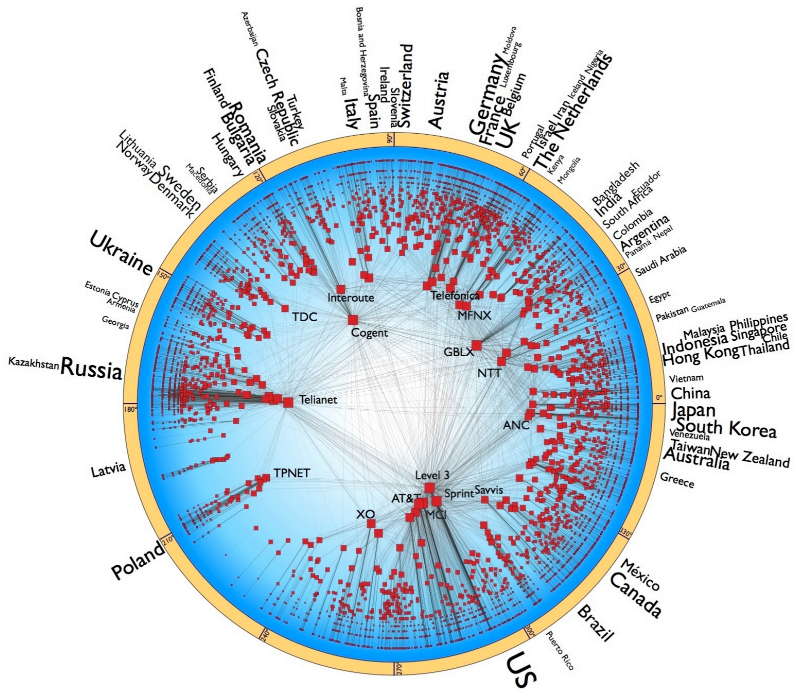
1: Connecting (few) computers: e-mail, file transfer, remote login.
2: Connecting larger number of computers: sharing information (WWW).
3: Connecting wireless and mobile devices.
4: Connecting people: social networks.
5: Connecting objects: Information-Centric Networks (ICNs),
Internet of Things (IoT),
Context-Aware Networking.

Internets of the future: a vision

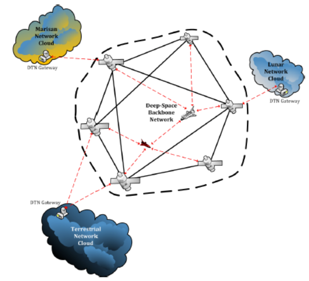
"Sorry it's taking so long to load. I'm still on dial-up."

What does the future hold?

Internets of the future: a vision



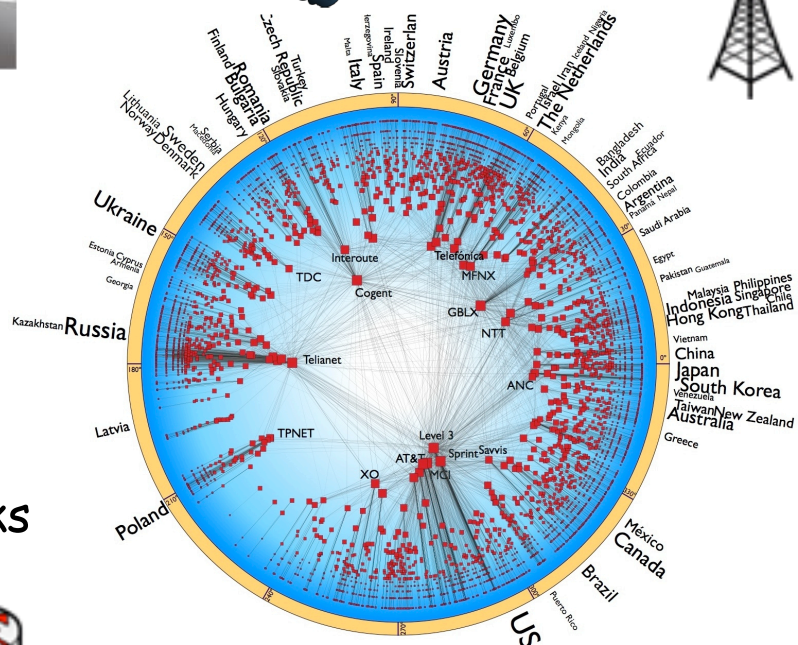
Internets of the future: a vision



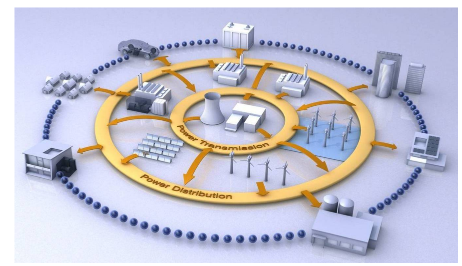
Interplanetary networks

Smart home

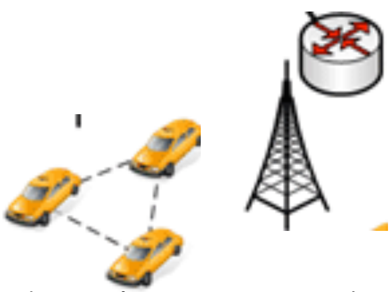
Wireless mesh network



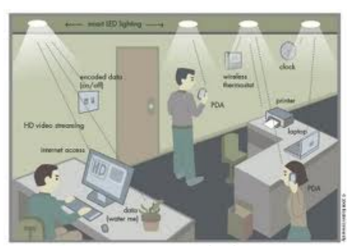
Mobile ad-hoc networks



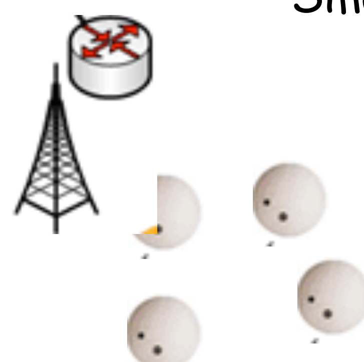
Smart grid



Vehicular networks



Smart office



Sensor networks

Driving forces behind future internets

Networked society

- User centricity
- Data centricity
- Increasing number and diversity of services/ apps
- Massive traffic volumes
- Massive number of devices

Technology drivers

- Automation everywhere!
- Resource and energy efficiency.
- Virtualization (e.g., clouds, data centers)
- New hardware/ communication technologies (e.g., 5G)
- New software technologies (SDN, NFV)

Adapted from IEEE NetSoft 2017 Tutorial
Rostami, Rothenberg, Obraczka

The “push from above”: diverse set of applications and services

BROADBAND EXPERIENCE EVERYWHERE, ANYTIME

SMART VEHICLES, TRANSPORT & INFRASTRUCTURE

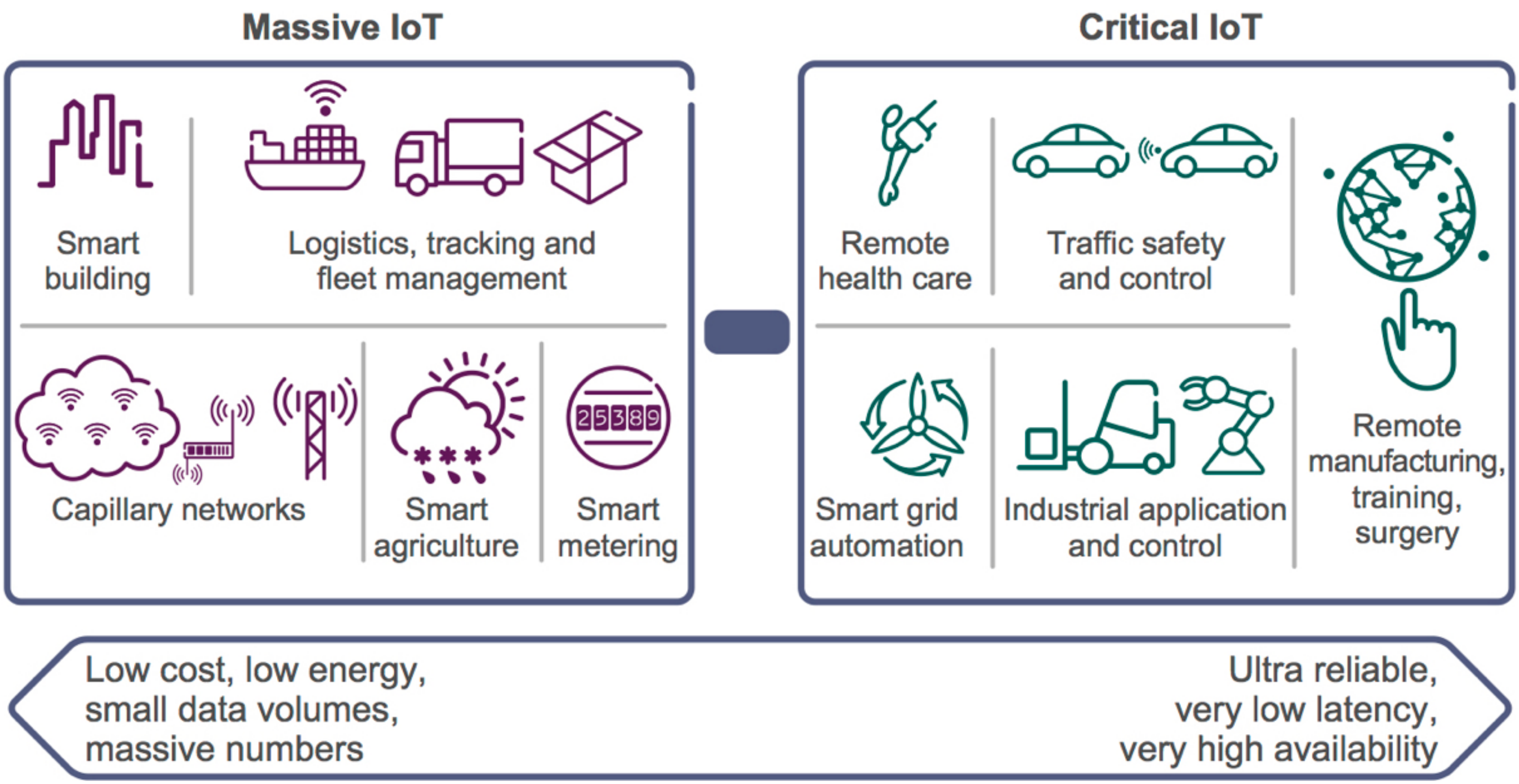
MEDIA EVERYWHERE

CRITICAL CONTROL OF REMOTE DEVICES

INTERACTION HUMAN-IOT

Adapted from IEEE NetSoft 2017 Tutorial
Rostami, Rothenberg, Obraczka

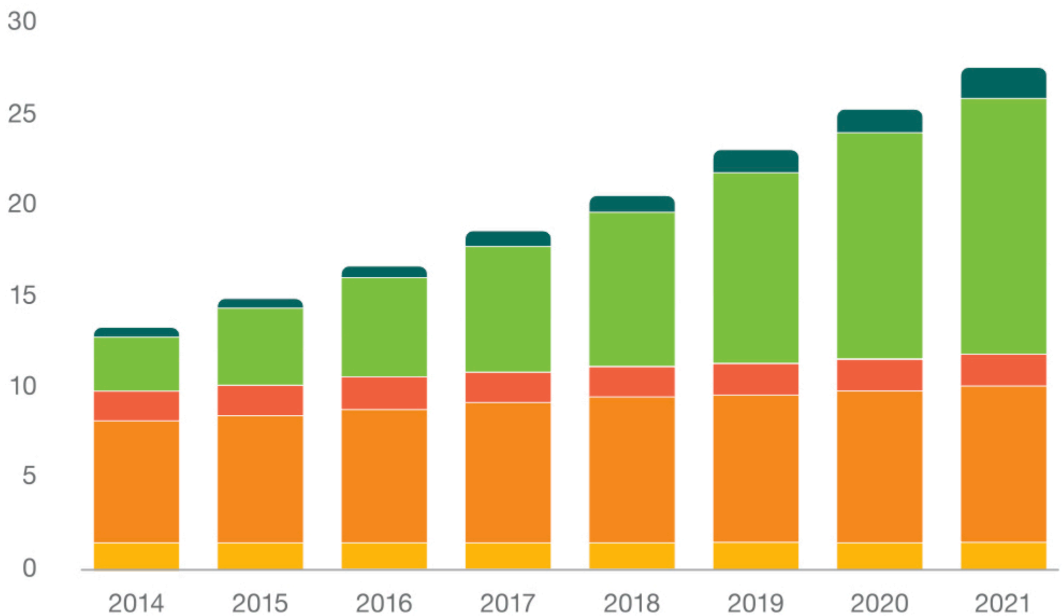
Diverse Requirements: IoT



Adapted from IEEE NetSoft 2017 Tutorial
Rostami, Rothenberg, Obraczka

The "push from below": IoT to surpass mobile phones in 2018

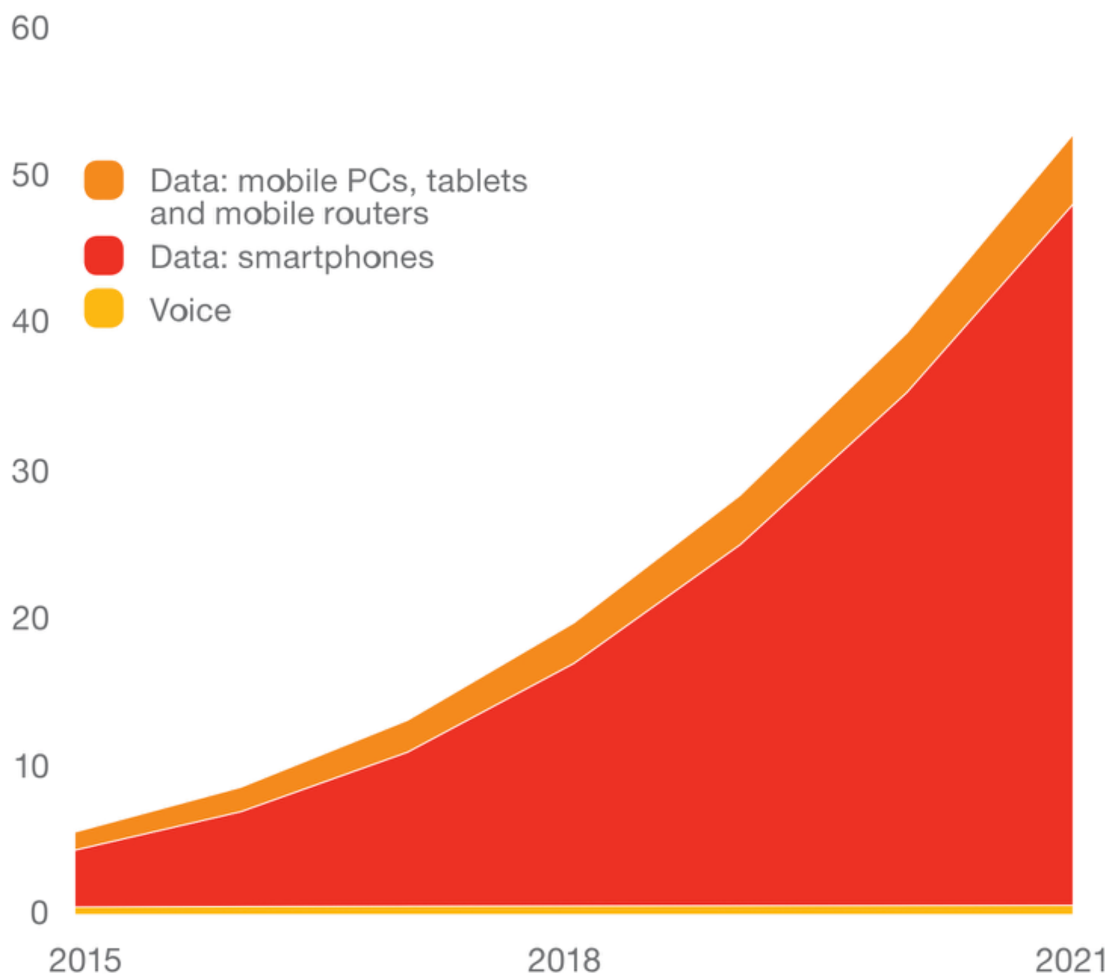
Connected devices (billions)



	15 billion (2015)	28 billion (2021)	CAGR 2015–2021
Cellular IoT	0.4	1.5	27%
Non-cellular IoT	4.2	14.2	22%
PC/laptop/tablet	1.7	1.8	1%
Mobile phones	7.1	8.6	3%
Fixed phones	1.3	1.4	0%

source: Ericsson Mobility Report

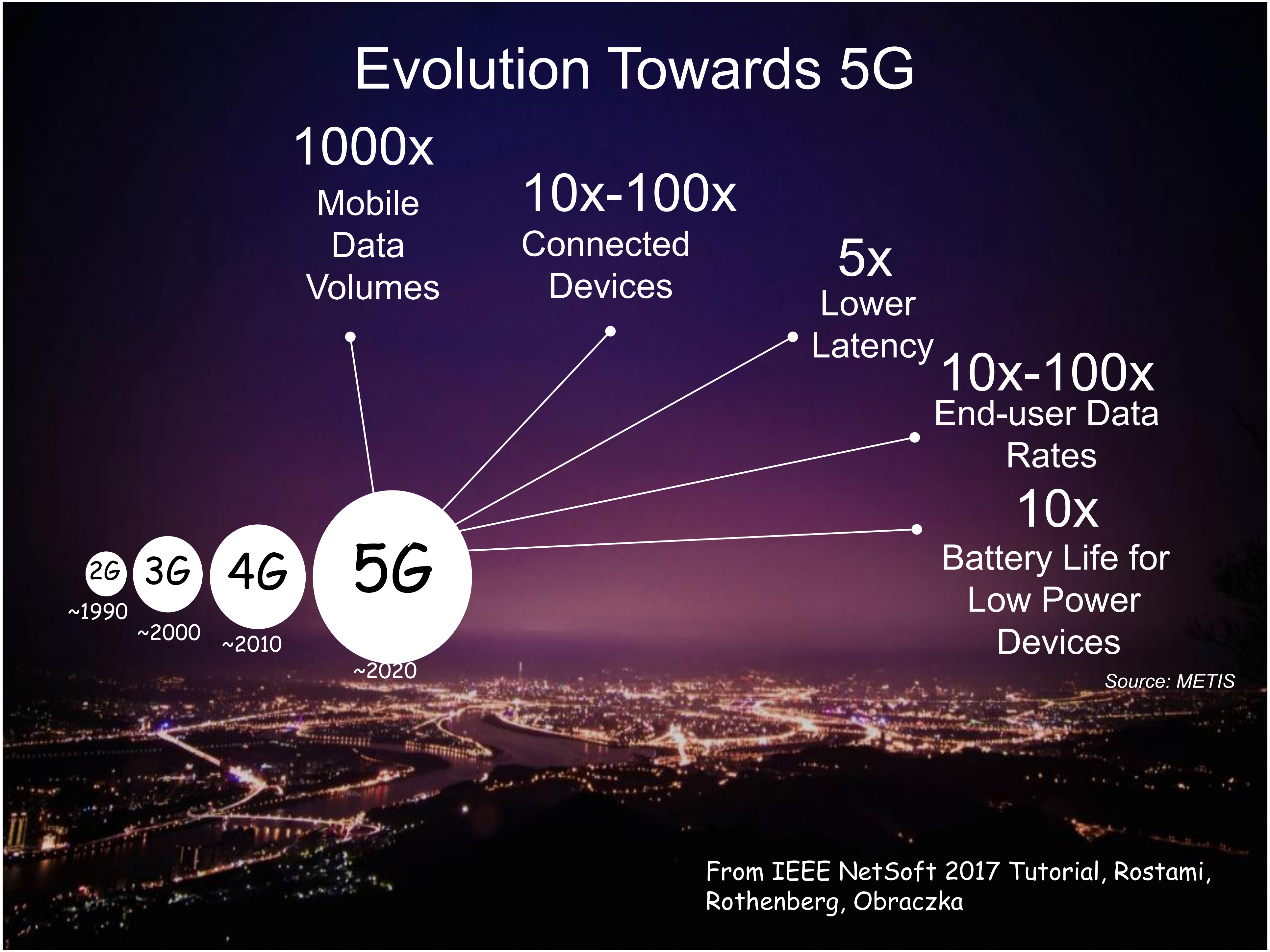
Global mobile traffic



12X growth in smartphone traffic

~ 90% of mobile traffic traffic from smartphones by end of 2021

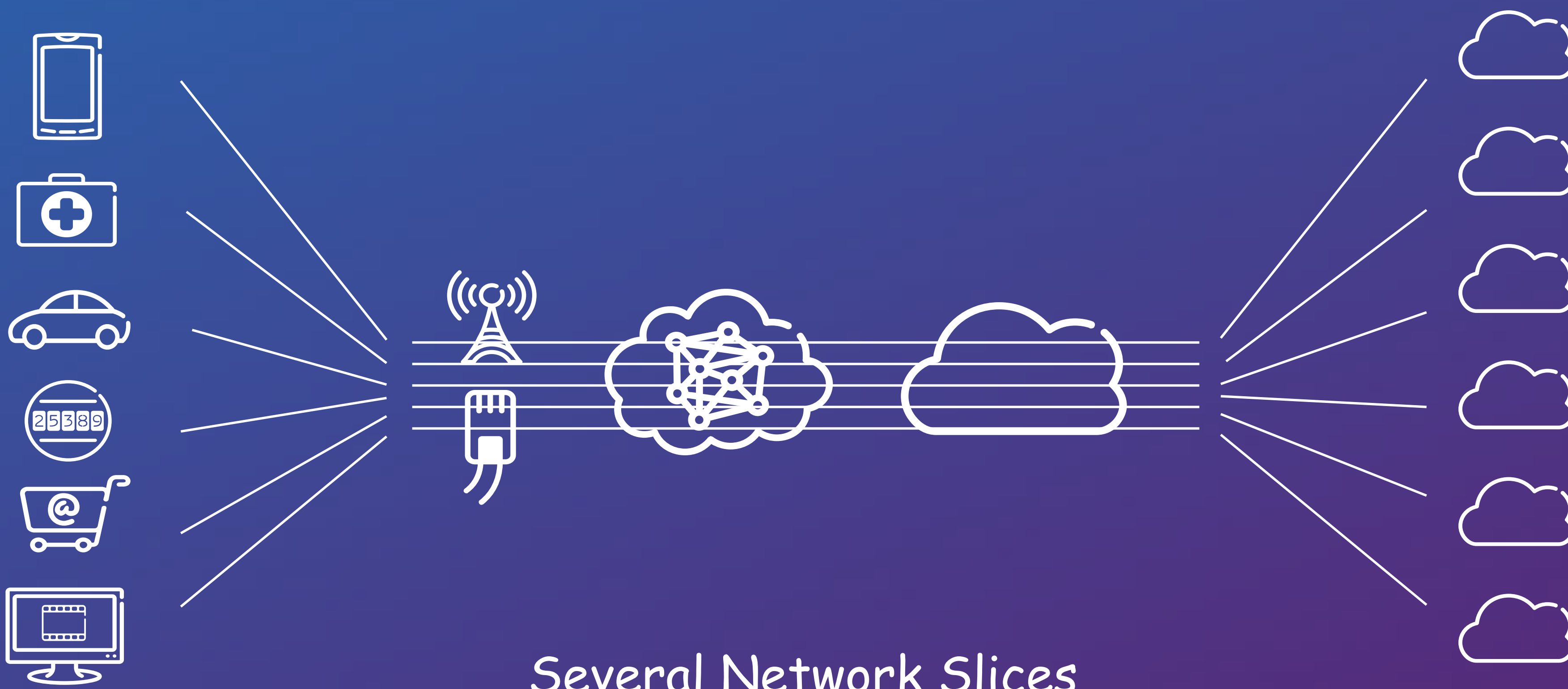
source: Ericsson Mobility Report


Evolution Towards 5G
1000x
Mobile Data Volumes
10x-100x
Connected Devices
5x
Lower Latency
10x-100x
End-user Data Rates
10x
Battery Life for Low Power Devices
2G
~1990
3G
~2000
4G
~2010
5G
~2020
Source: METIS
From IEEE NetSoft 2017 Tutorial, Rostami, Rothenberg, Obraczka

Challenges

- Scalability
  - As of early 2013, ~1.5 billion connected PCs and ~1 billion Internet-enabled mobile phones.
  - By 2020, ~50-100 billion Internet-connected devices.
- Heterogeneity
  - Devices
  - Networks
  - Services
- Autonomy and administrative decentralization

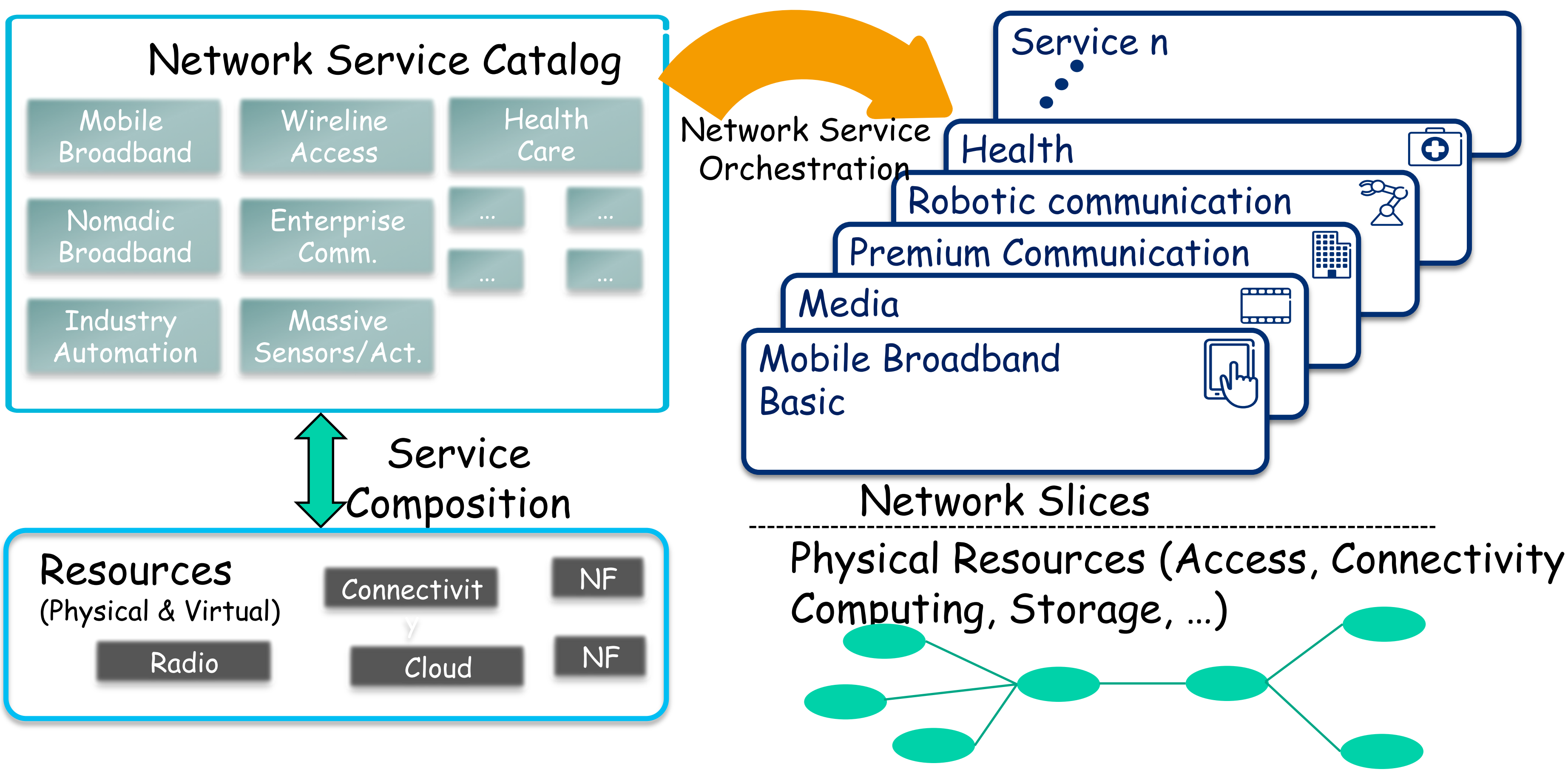
One network – multiple service/application domains



Several Network Slices

Adapted from IEEE NetSoft 2017 Tutorial, Rostami, Rothenberg, Obraczka

Network as a service



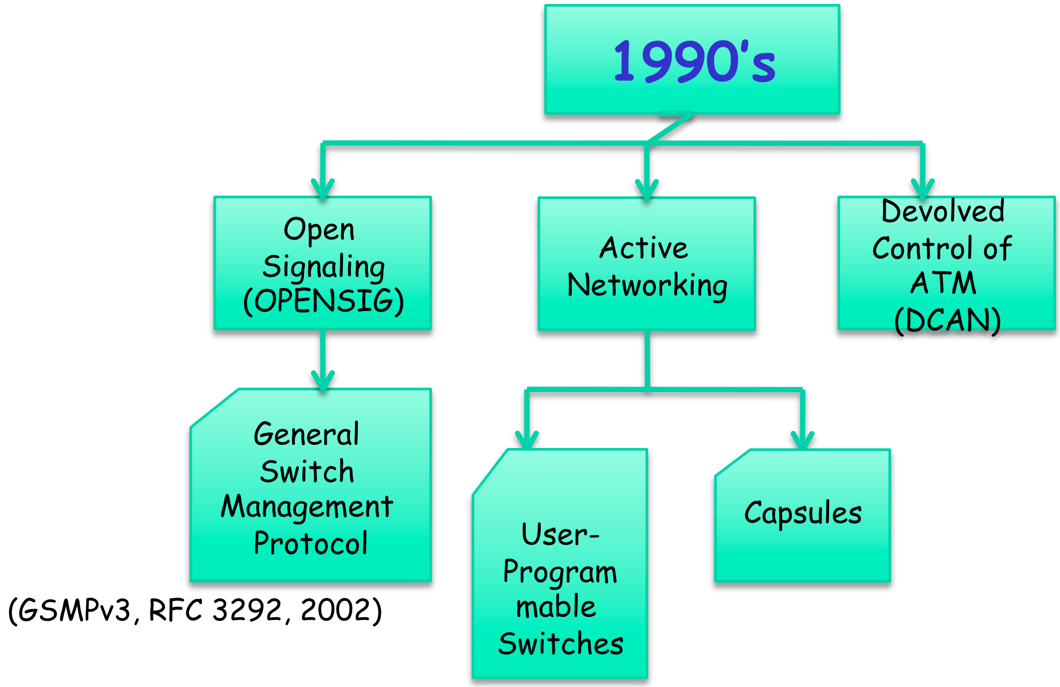
Adapted from IEEE NetSoft 2017 Tutorial, Rostami, Rothenberg, Obraczka

Network as a service: how?

Network as a service: how?

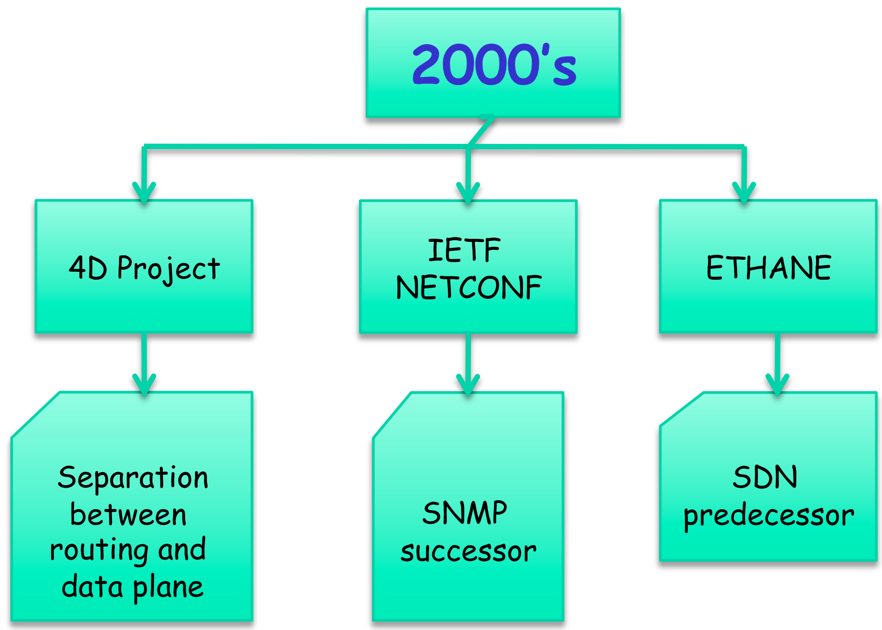
- Network programmability
- Control- and data plane separation
- Networking function virtualization

Programmable Networks: Some History (1)



Adapted from IEEE NetSoft 2017 Tutorial, Rostami, Rothenberg, Obraczka

Programmable Networks: Some History (2)



Adapted from IEEE NetSoft 2017 Tutorial,
Rostami, Rothenberg, Obraczka

Software-Defined Networking Architectures

IETF ForCES

- Forwarding Element (FE) and Control Element (CE)
- Both reside in the network device
- FE and CE communicate using the ForCES protocol

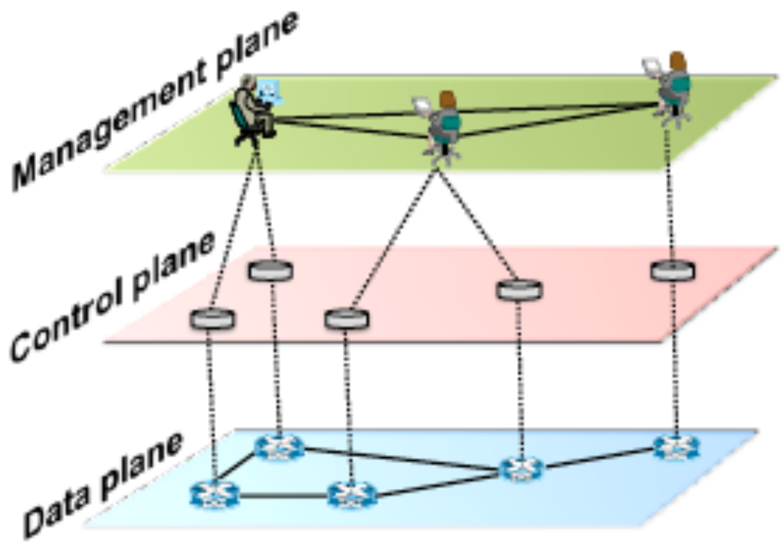
ONF OpenFlow

- Decoupling between control- and data planes
- Controller and switch communicate using the OpenFlow protocol

Adapted from IEEE NetSoft 2017 Tutorial, Rostami, Rothenberg, Obraczka

What’s Software-Defined Networking?

Network’s Functional Planes



Source: “Software-Defined Networking: A Comprehensive Survey”, Kreutz et al., https://arxiv.org/pdf/1406.0440.

What's Software-Defined Networking?

- Main principle: decouple data plane from control plane.

Why Software-Defined Networking?

- The Internet has been the victim of its own success!
- Extremely hard to configure, manage, and evolve.
- "Vertically integrated": tight coupling of control- and data planes embedded/ distributed in network devices.
- Proliferation of specialized "middleboxes".

Source: N. McKeown, Stanford, ONF

Adapted from IEEE NetSoft 2017 Tutorial, Rostami, Rothenberg, Obraczka

Why Software-Defined Networking?

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Software-Defined Networking to the rescue!

› Separation of control plane from data plane.
  - Network control "logically centralized" in the **controller**.
  - Forwarding hardware simplified.

› Programmable networks to facilitate management and control and combat "network ossification".

› Data plane "commoditization".

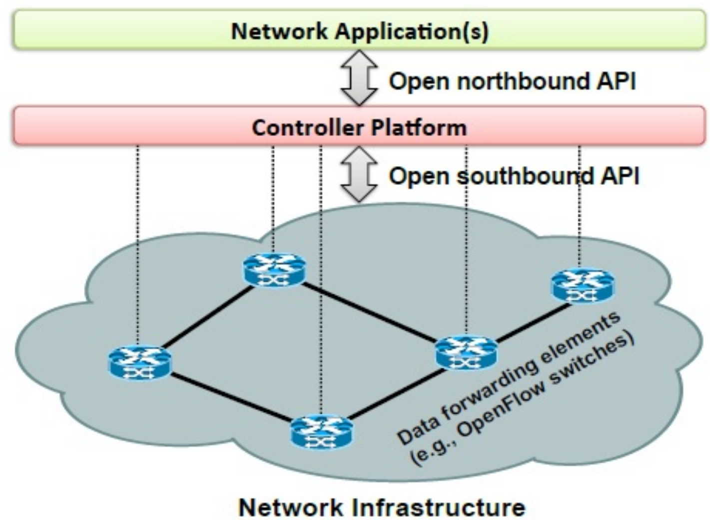
Adapted from IEEE NetSoft 2017 Tutorial, Rostami, Rothenberg, Obraczka

SDN: Definitions, Concepts, and Terminology

SDN refers to software-defined networking architectures where:

- Data- and control planes decoupled from one another.
- Data plane at forwarding devices managed and controlled remotely by a "controller".
- Well-defined programming interface between control- and data planes.
- Applications running on controller manage and control underlying data plane

SDN architecture



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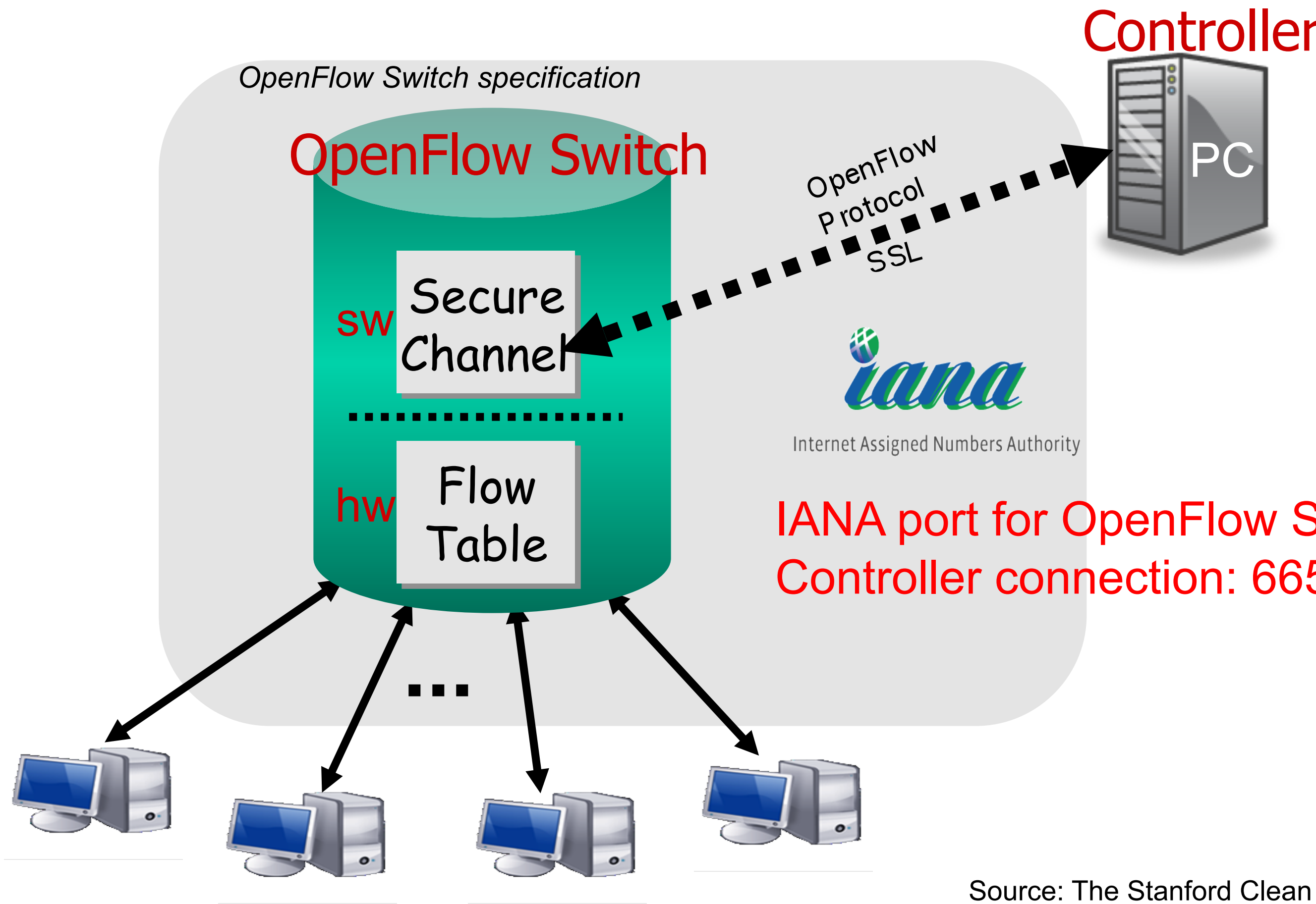
"Software-Defined Networking: A Comprehensive Survey", Kreutz et al., https://arxiv.org/pdf/1406.0440.

ONF OpenFlow Architecture



IANA port for OpenFlow Switch-Controller connection: 6653

Source: The Stanford Clean Slate Program, http://cleanslate.stanford.edu

SDN Definitions

- **"The SDN architecture decouples the network control and forwarding functions enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services."** Open Networking Foundation (opennetworking.org)

- **"Software Defined Networking (SDN) refactors the relationship between network devices and the software that controls them. Opening up the interfaces to programming the network enables more flexible and predictable network control, and makes it easier to extend the network with new functionality."** *ACM Sigcomm Simposium on Software-DefinedNetworking Research 2016.*

Research at the UCSC Internetwork Research Group: iNRG (http://inrg.cse.ucsc.edu)

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- Motivated by vision of future internets.
- Design, develop, evaluate, deploy protocols and services targeting future internets.
- The Internet
- Wireless internetworking
  - Infrastructure-based
  - Infrastructure-less
    - Multihop ad-hoc networks (MANETs)
    - Wireless sensor networks (WSNs)
    - Disruption-tolerant networks (DTNs)
  - Heterogeneous networks

Flexible and Programmable Network Control for Future Internets

Use Case: Intelligent Transportation System (ITS)

Intelligent Transportation System (ITS)

- Vehicular Communication :
  - Information to self drive.
  - Co-ordinate traffic flow.
  - Communicate road conditions.
  - Collision avoidance.

- Vehicular Communication types
  - Vehicle to Vehicle (V2V)
  - Vehicle to Infrastructure (V2I)

Message Dissemination in ITS

Challenges:

- Low latency
  - Low latency requirements (typically in order of tens of milliseconds for some types of messages).
- Reliability
  - ITS message dissemination needs to be highly reliable.
- Scalability
  - Data traffic is expected to grow significantly as well as number of connected cars and devices.
- Geographic Decentralization
  - Network connectivity in different geographical areas poses challenges for ITS.

Existing approaches and limitations

Low latency and efficient protocols for ITS

❒ IEEE 802.11p and LTE

- Enhancement to 802.11 for enhanced data rate for V2V and V2I
- 802.11p suffers from scalability issues[1]
- LTE has latency concerns due to centralized architecture[2]

Scalable architectures

❒ Software Defined Networking (SDN) and Software Defined Vehicular Ad hoc NETwork (SD-VANET)[3][4]

- SDN and SD-VANETs increase network programmability by decoupling control and data plane.
- They either rely on centralized control plane or static control distribution.

Our approach: Dynamically Distributed ITS (D2-ITS)

Flexible and extensible framework that can

- Dynamically distribute network control to address scalability, delay intolerance, and decentralization requirements of ITS.

First framework to employ a logically distributed control plane

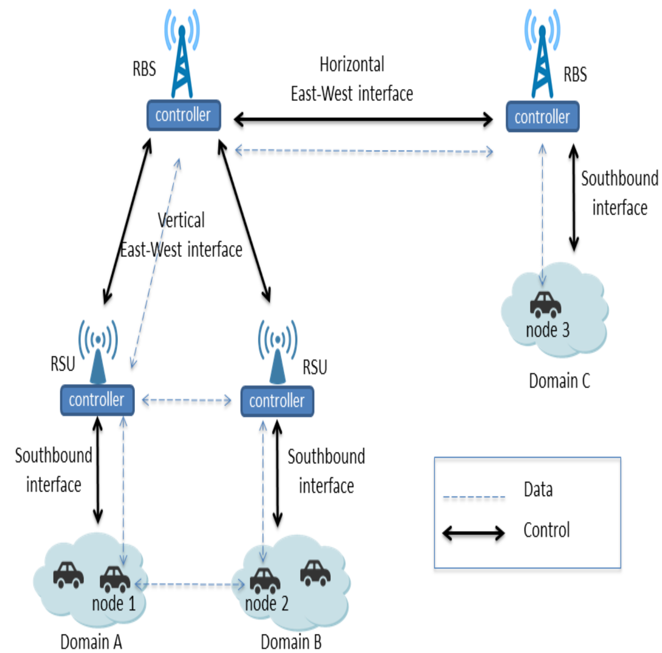
- Control plane decoupled from data plane
- Control hierarchy that dynamically adjusts to environment and network conditions.

“Dynamically Distributed Network Control for Message Dissemination in ITS”, Anuj Kaul, Katia Obraczka, Mateus A. S. Santos, Christian E. Rothenberg, Thierry Turletti, to appear in IEEE DS-RT 2017.

D2-ITS Architecture

Components of D2-ITS

1. Vehicles
   - Equipped with software switch.
2. Controllers co-located with
   - Road Side Unit (RSU)
     - Vehicles communicate with RSU.
     - Also equipped with software switch
   - Radio Base stations (RBS)
     - RSUs communicate with RBS through a back haul network
3. Domain
   - RSU's domain is defined by vehicles it controls.
4. Control Plane
   - Vehicle-controller (e.g., RSU): enabled by southbound interface
   - Controller-controller: enabled by (vertical and horizontal) east-west communication
5. Data Plane
   - Data is forwarded according to routing/forwarding policies established by the domain's controller (e.g., RSU)
   - RSU and RBS can be part of data forwarding or not.



Example D2-ITS scenario

Road Hazard Warning (RHW)

- Road Hazard Warning (RHW) [5], [6]
  - Event-based road message dissemination service specified by the European Telecommunications Standards Institute (ETSI).

- Message types
  - Decentralized Environmental Notification Messages (DENMs)
    - Mainly used to provide the necessary alerts in the case of emergency situations (e.g., eminent risk of collision) or warnings, e.g., in the event of a road congestion. As such, DENMs should be conveyed through the ITS infrastructure and delivered to road users in the geographic area affected by the event.
  - Cooperative Awareness Messages (CAMs)
    - Signaling messages.
    - Carry information about vehicle location, vehicle type, as well as time of day, vehicle speed, etc.

Message types in D2-ITS

DENMs

- Emergency
  - Highest delivery priority message.
  - Time-sensitive data plane messages sent by vehicles to their connected controller to convey information about nearby accidents, eminent risks, etc.
  - Controllers flood the emergency message in their relevance area, generally a domain of the controller.

- Warning
  - Lower priority message than Emergency, carrying information like road congestion, traffic flow.
  - Warnings are disseminated by controllers to vehicles within their relevance area.
  - Depending upon the type of warning and the extension of the area it affects, the controller can also forward such message to peer controllers, which in turn will decide how to forward the message further.

CAMs

- Location Update
  - Carry information about vehicles such as their current location, speed, etc.
  - Controllers use location updates to compute relevance areas, compute and install routes in vehicles

User Addition Requests

- Sent by a vehicle to the controller to which the vehicle trying to connect.
- Serves to authenticate the vehicle with the controller.

Controller HELLO

- control plane messages used to advertise controller presence and build peering relations between pairs of controllers

Message dissemination in D2-ITS

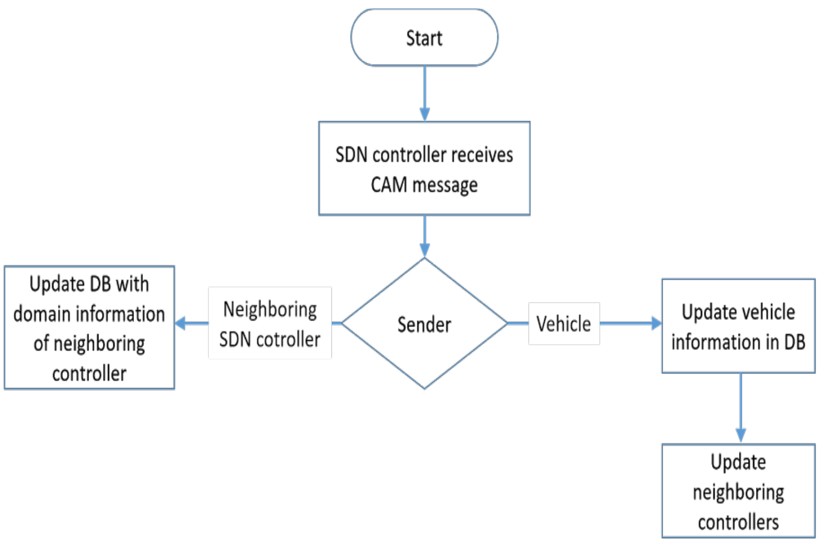


Fig 2: CAM dissemination

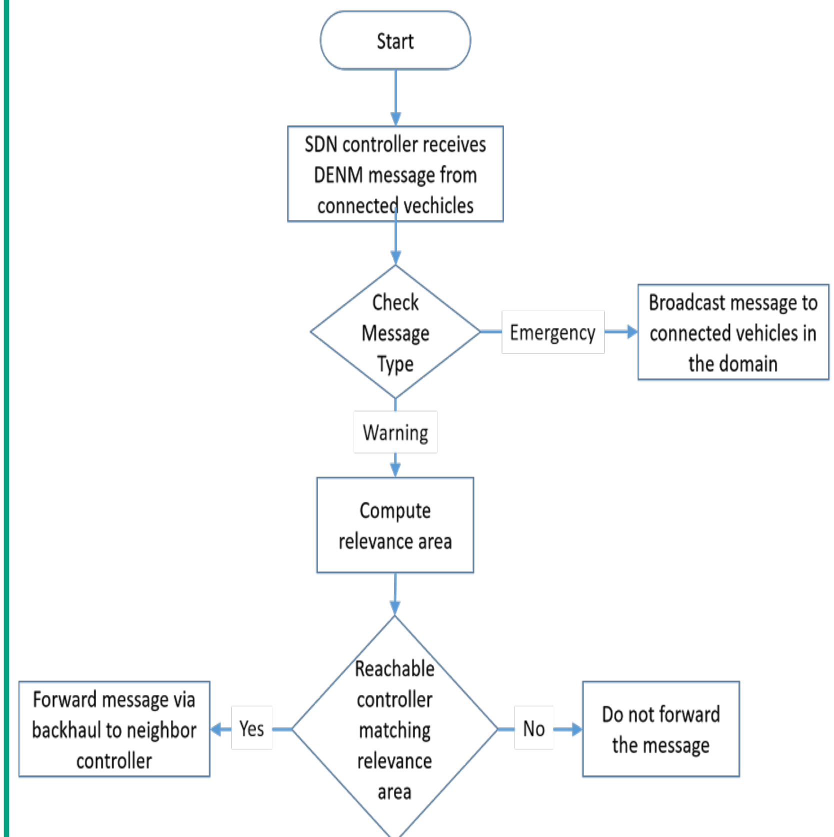
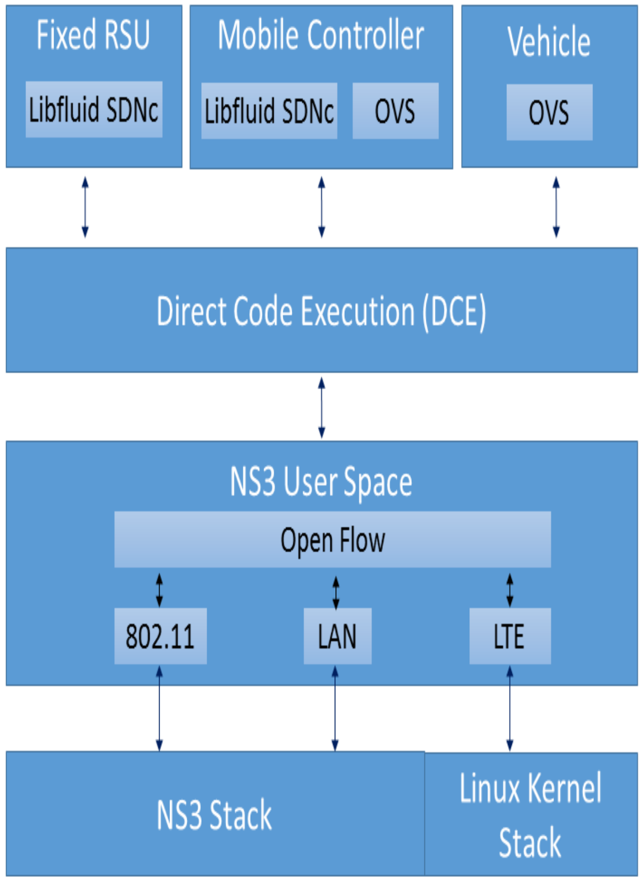


Fig 3: DENM dissemination

D2-ITS prototype

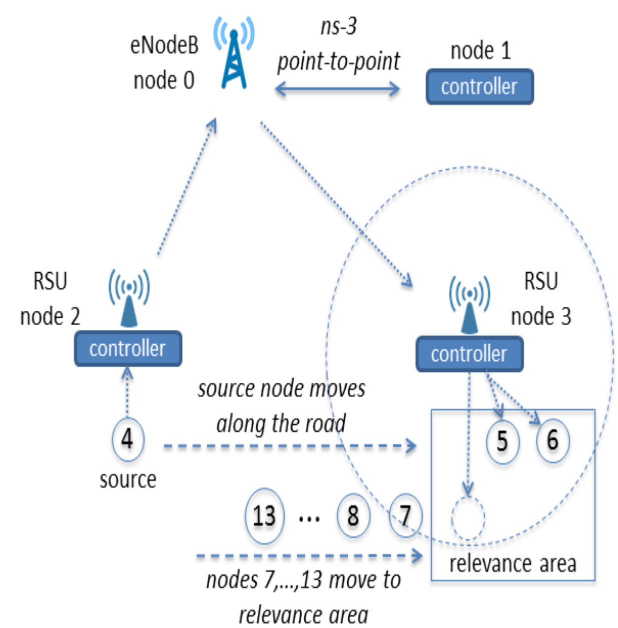
D2-ITS component implementation

- Fixed Controller
  - RSU are simulated Libfluid SDN controller implementation
- Mobile Controller
  - Mobile controller (Vehicle) is implemented using Libfluid controller and openvswitch(OVS).
  - If vehicle is acting as controller, then libfluid controller is enabled otherwise by default vehicle is enabled with OVS
- DCE and NS-3
  - Direct Code Execution and NS3 stacks are used to support different underlying protocols like 802.11, LAN and LTE.



D2- ITS scenarios - Decentralized

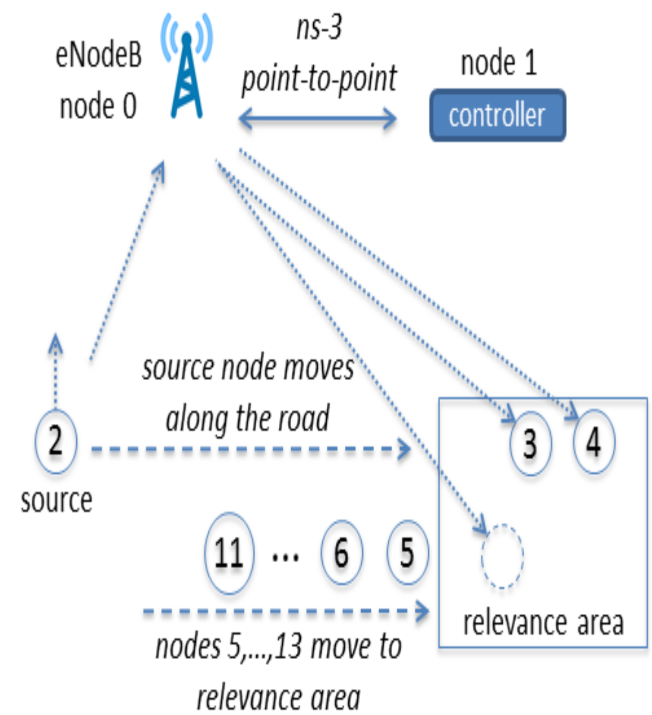
- Set up
  - Two stationary RSUs (node 2 and node 3), each co-located with a controller, are interconnected through a wireless network.
  - Vehicles in an RSU's range connect to the controller hosted by the RSU over IEEE 802.11 ad hoc mode;
  - RSUs communicate through a point-to-point backhaul network.
- Message generation
  - Vehicles send periodic RHW messages that are either warning or emergency messages and are conveyed over V2I communication.
- Vehicle mobility
  - we simulate platoon of vehicles traveling on the road with a certain speed.
  - The source node (node 4), which is also moving, sends warning and emergency messages.
  - Mobile vehicles are moving towards the relevance area of RSU node 3.
  - Mobility simulated using Simulation of Urban Mobility (SUMO).



Decentralized control scenario

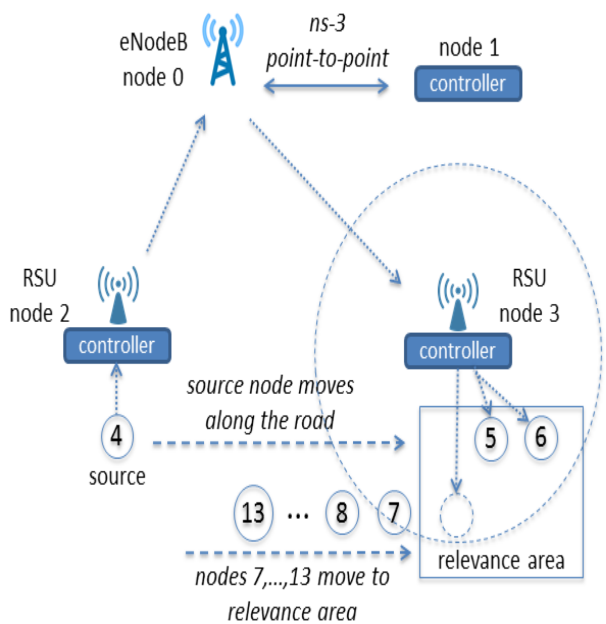
D2- ITS scenarios - Centralized

- Set up
  - Vehicles are associated to a single network-wide controller using the cellular network. In particular, as shown in Figure , we use an LTE network where the LTE base station, eNodeB, (node 0) is connected to the centralized controller through a backhaul network.
- Message generation
  - Vehicles send periodic RHW messages that are either warning or emergency messages and are conveyed over V2I communication.
- Vehicle mobility
  - we simulate platoon of vehicles traveling on the road with a certain speed.
  - The source node(node 2), which is also moving, sends warning and emergency messages
  - Mobility simulated using Simulation of Urban Mobility (SUMO).

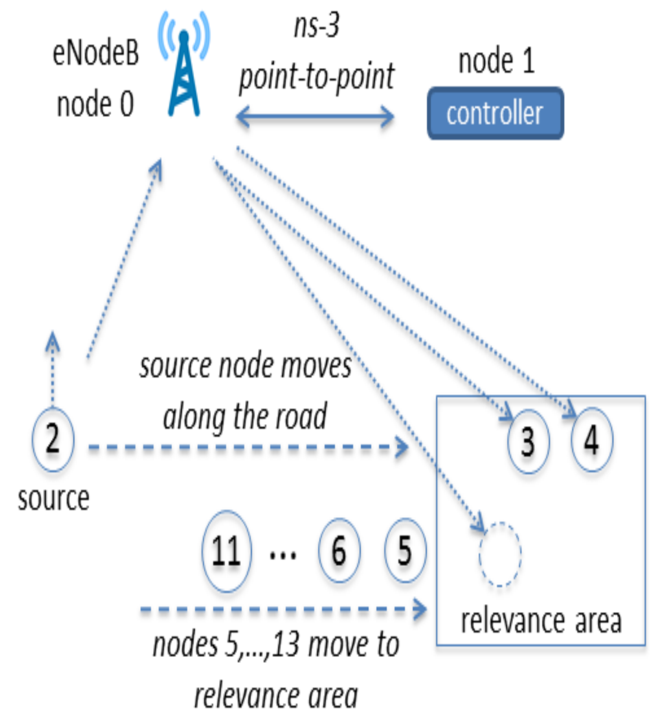


Centralized control scenario

D2-ITS experimental scenarios



Decentralized control: control hierarchy using controllers at RSUs and LTE BS; Periodic RHW messages sent (both emergency and info); platoon of vehicles and source node moving.



Centralized control: single controller using LTE to communicate;

Parameter	D-ITS	C-ITS
Simulation time	300 s	300 s
Number of nodes	14	12
Node speed	10.15 m/s	10.15m/s
Event report interval (Information)	3	3
Event report interval (Emergency)	7	7
Communication	802.11 ad hoc	LTE
Bandwidth	11 Mbps	25 Mbps
Distance between RSUs	740m	NA
Estimated RSU range	145m	NA
Backhaul delay	100ms	100 ms
Backhaul data rate	2 Mbps	2 Mbps
Grid size	1000 X 800m	1000 X 800m

Latency D-ITS

Observations

1. Emergency message
   - Average Latency for emergency message is 18 msec.
   - Fig 7 emergency messages are localized to a single domain, resulting in delivery with low latency
   - Stationary vehicle does not receive emergency messages until time 145 seconds, i.e., when source node finds itself in the same domain as its (stationary) destination
2. Information message
   - Average latency for warning messages depends upon the location of the vehicle.
   - In Fig 6, Average latency up to 116 msec till source node is connected to RSU(node2) and average latency drops to ~ 18 msec once source node connects to RSU node 3.
3. Outliers:
   - Vehicle mobility increases the chance of such anomaly in the simulated experiment.
   - Latency can increase as vehicles reach the edge of the RSU coverage area
4. Overhead
   - D-ITS scenario is only 6.5% higher than C-ITS's overhead.

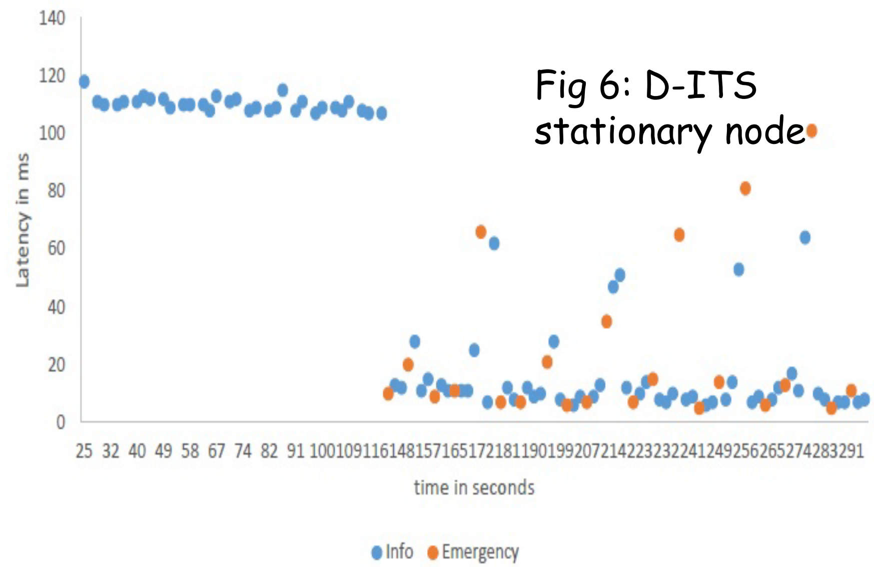


Fig 6: D-ITS stationary node

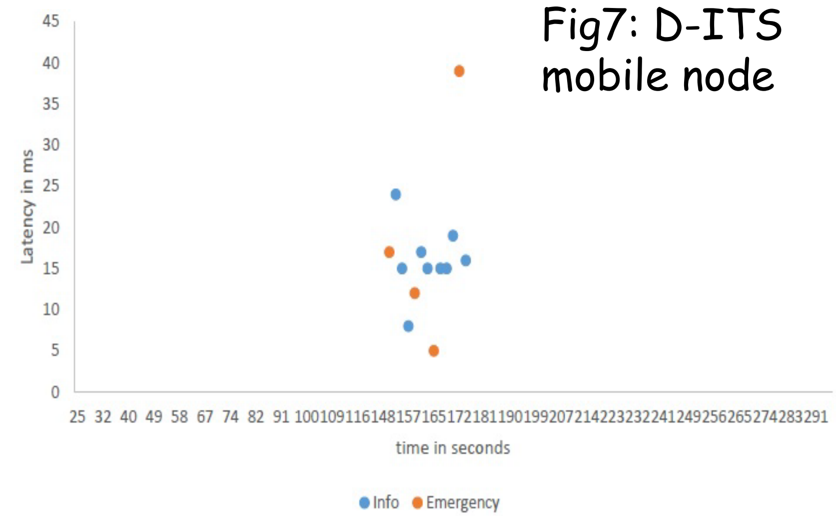


Fig7: D-ITS mobile node

Latency C-ITS

Observations

1. There is no difference in delivery latency for stationary- or mobile nodes.
2. Delivery latency is constant throughout the experiment.
3. There is no difference in latency for emergency or warning messages.
4. Average latency for both the messages is 142 msec.

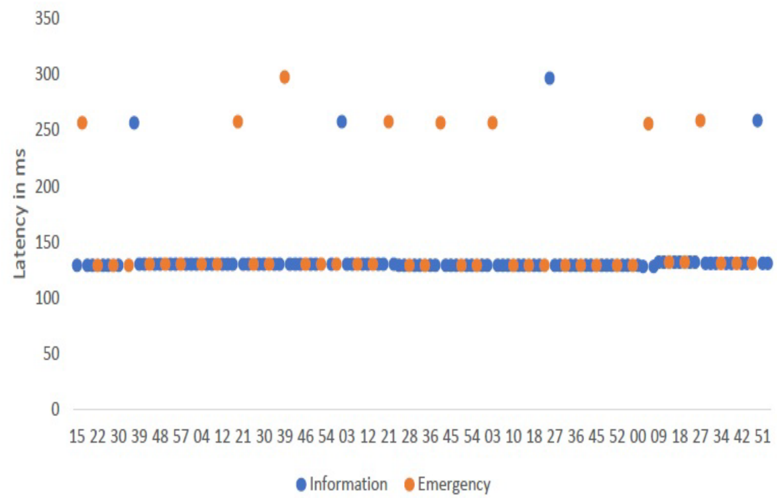
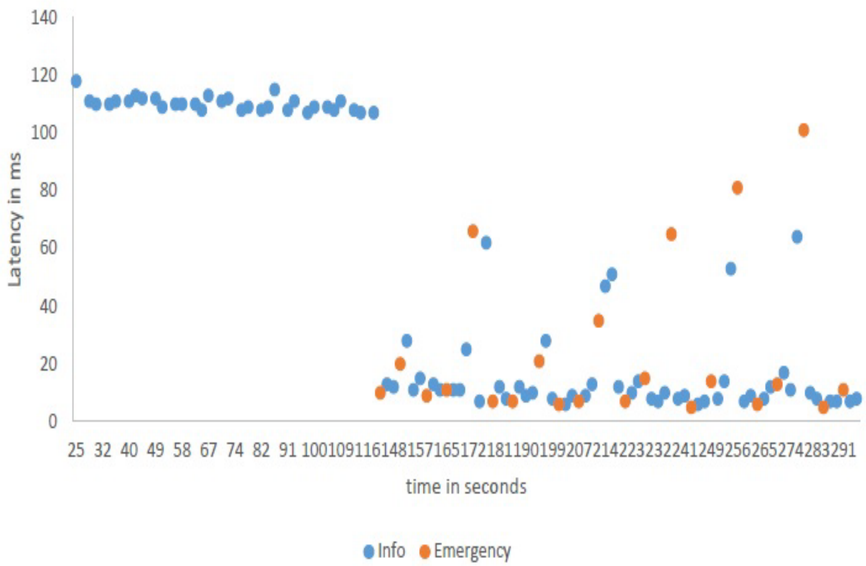
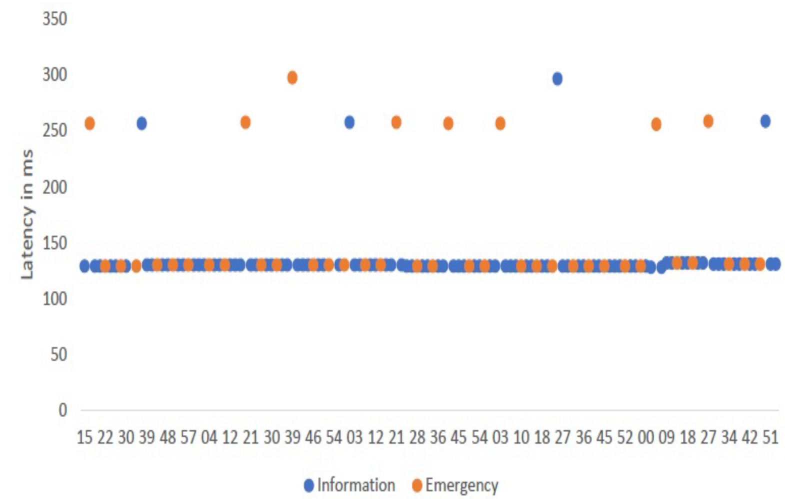


Fig 8: C-ITS mobile node

Latency results





D-ITS: Average Latency for emergency message is 18 msec; Average latency for warning messages depends upon vehicle's location. Here average latency up to 116 msec till source is connected to RSU and drops to ~ 18 msec once source re-connects to RSU.

C-ITS: There is no difference in latency for emergency or warning messages. Average latency for both messages is 142 msec.

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Ongoing work

- Handovers
- V2V communication
- Control plane load balancing and fault tolerance
- Security

References

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Smart Congestion Control for Delay and Disruption Tolerant Networks (DTNs)

Aloizio P. Silva, K. Obraczka, Scott Burleigh and Celso M. Hirata, "Smart Congestion Control for Delay- and Disruption Tolerant Networks", IEEE SECON 2016, London, UK, June 2016

Delay- Disruption Tolerant Networks

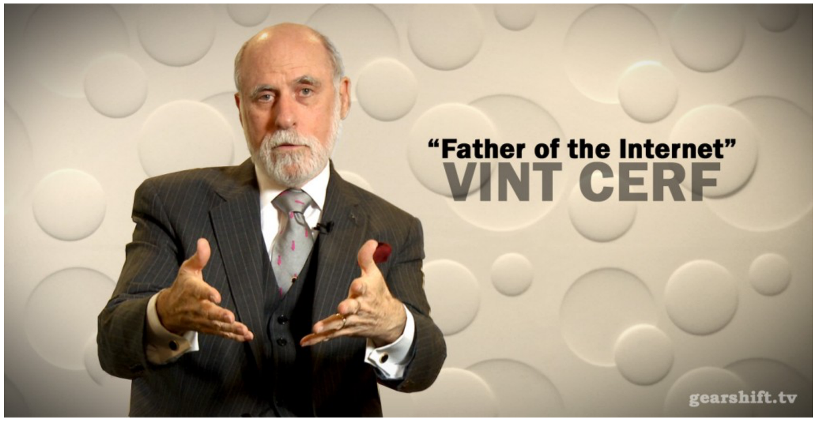
- Episodically connected.
- Provide access to information, people, and services even when physical connectivity is sporadic or disrupted frequently.
- Opportunistic use of available resources.
- Initial driving application:
  - Interplanetary internetworking (IPN).

IPN: Some History

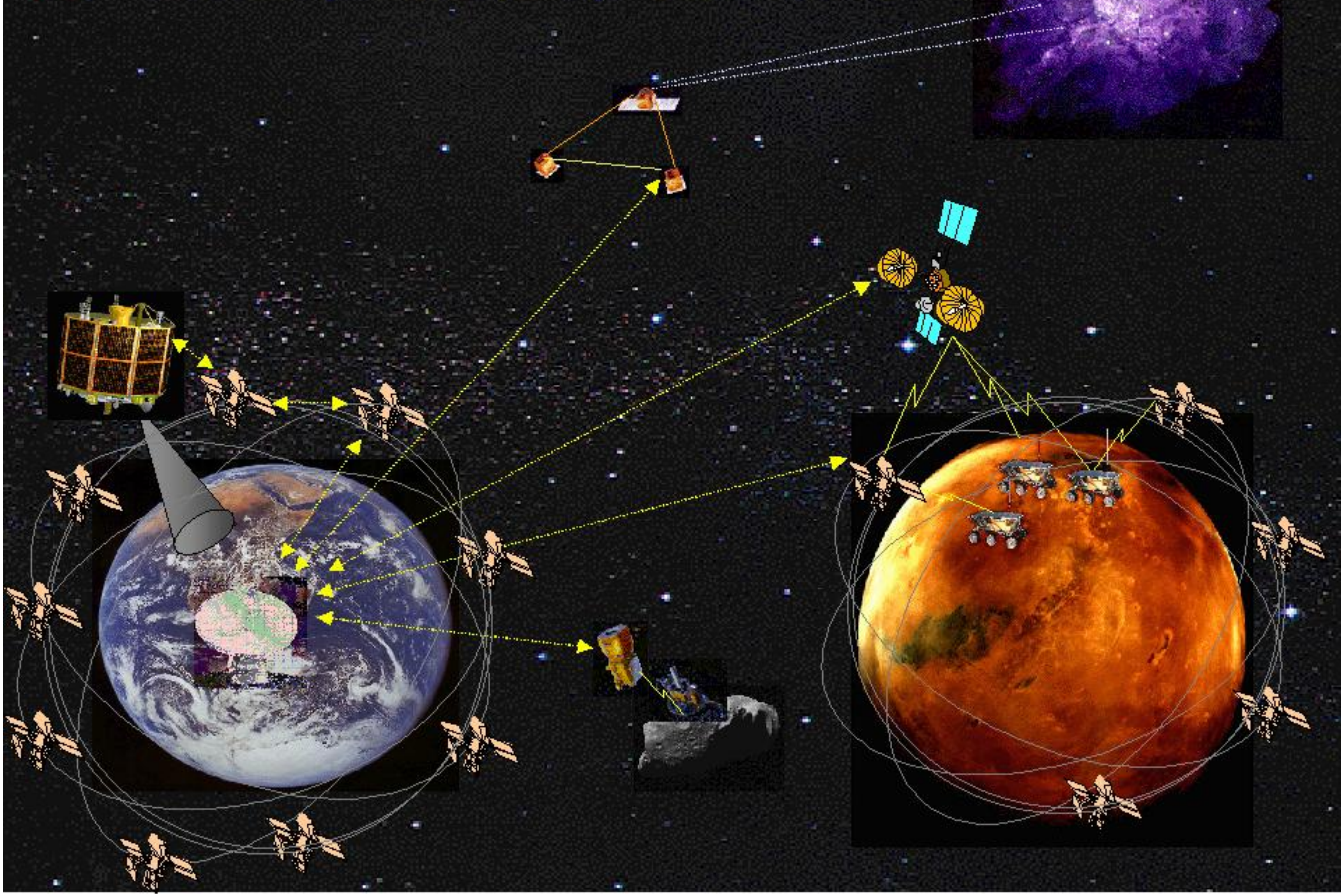
- NASA/JPL:
  - Internetworking in space.
  - One reusable network for all missions.
  - Gain from experience already acquired.

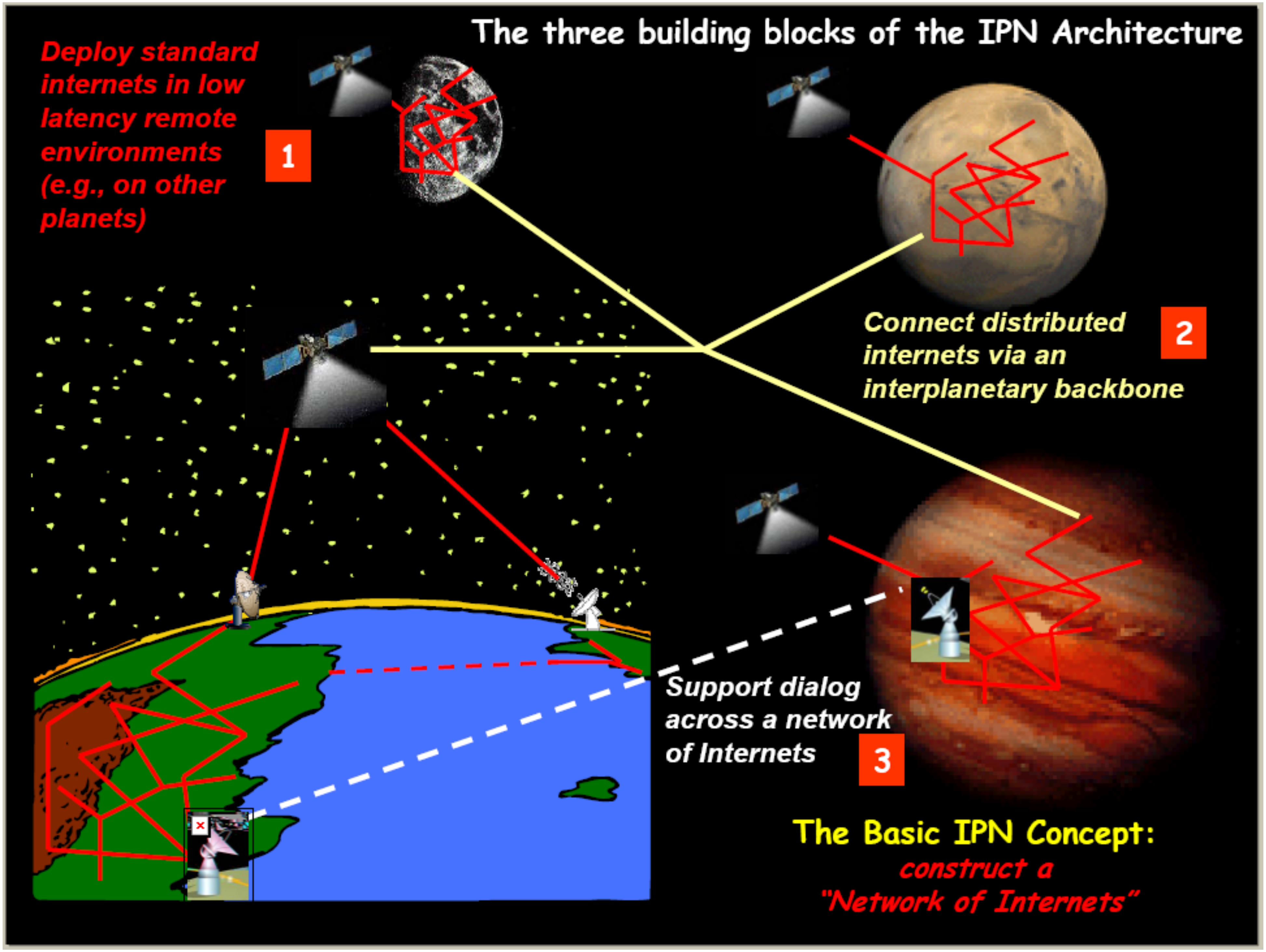
Interplanetary Internet (IPN)

- "to permit interoperation of the Internet resident on the Earth with other remotely located Internets resident in another planets or spacecraft in transit"



Interplanetary Internet




The three building blocks of the IPN Architecture
Deploy standard internets in low latency remote environments (e.g., on other planets)
1
Connect distributed internets via an interplanetary backbone
2
Support dialog across a network of Internets
3
The Basic IPN Concept:
construct a
"Network of Internets"

IPN Challenges

- Very long propagation delays.
- Heterogeneity:
  - Asymmetrical forward and reverse links.
  - Variable delays.
  - Error rates.
- High link error rates.
- Intermittent link connectivity, e.g., blackouts.
- Power, mass, size, and cost constraints for communication hardware and protocol design.

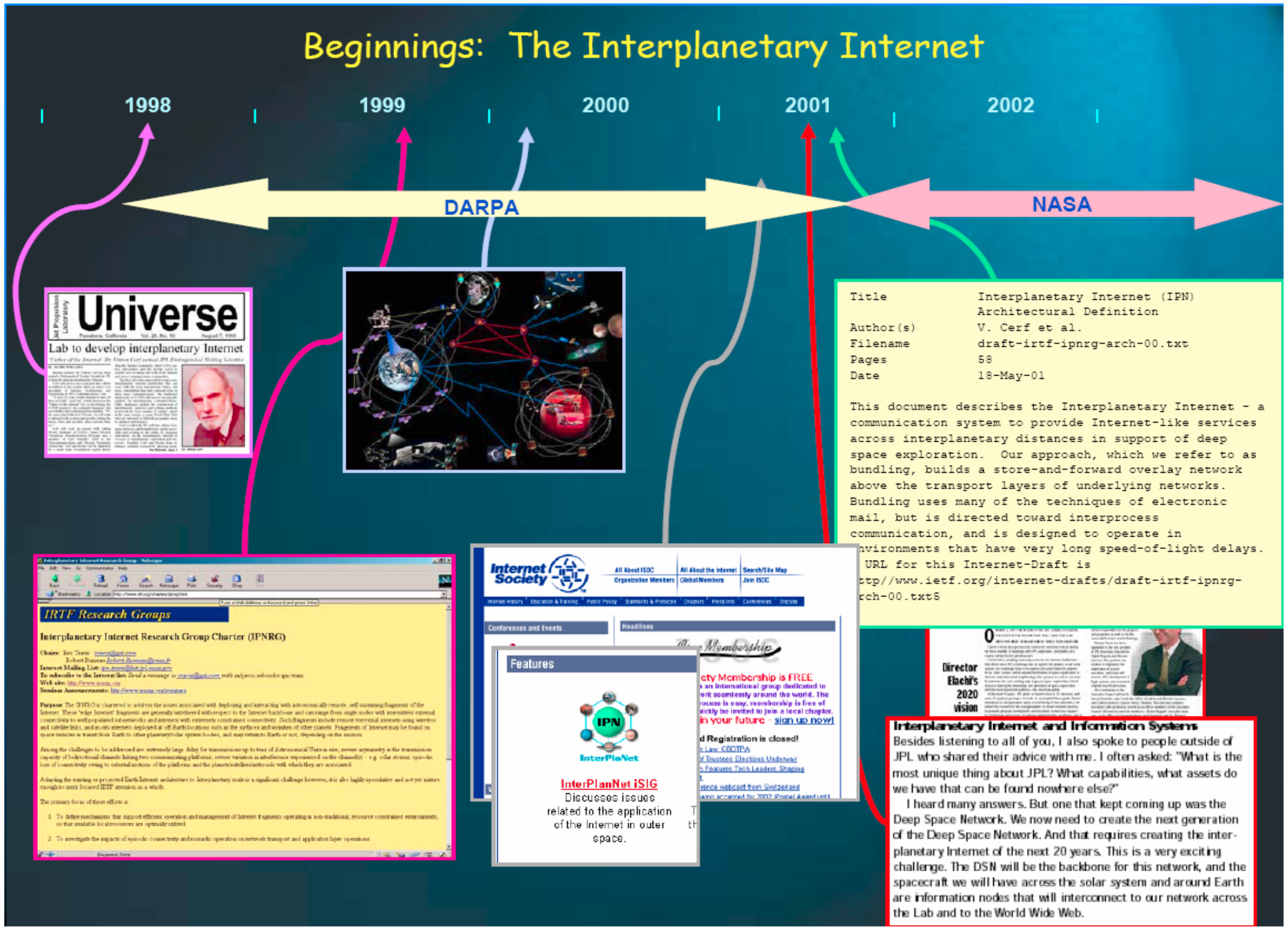
Use Internet Architecture?

Internet assumptions:

- Propagation delays comparable to transmission and queuing delays.
- End-to-end connectivity.
- Homogeneity (links and nodes).
- Processing and storage inside network is expensive.

Delay Tolerant Networking (DTN): History

(Source: "Delay Tolerant Networking," S. Burleigh et al, 24 April 2003)



DTN: Other Applications

(Source: "Delay Tolerant Networking," S. Burleigh et al, 24 April 2003)

DTN Applications

Disaster and Emergency Response

Tsunami

Earthquake

Wildlife Monitoring

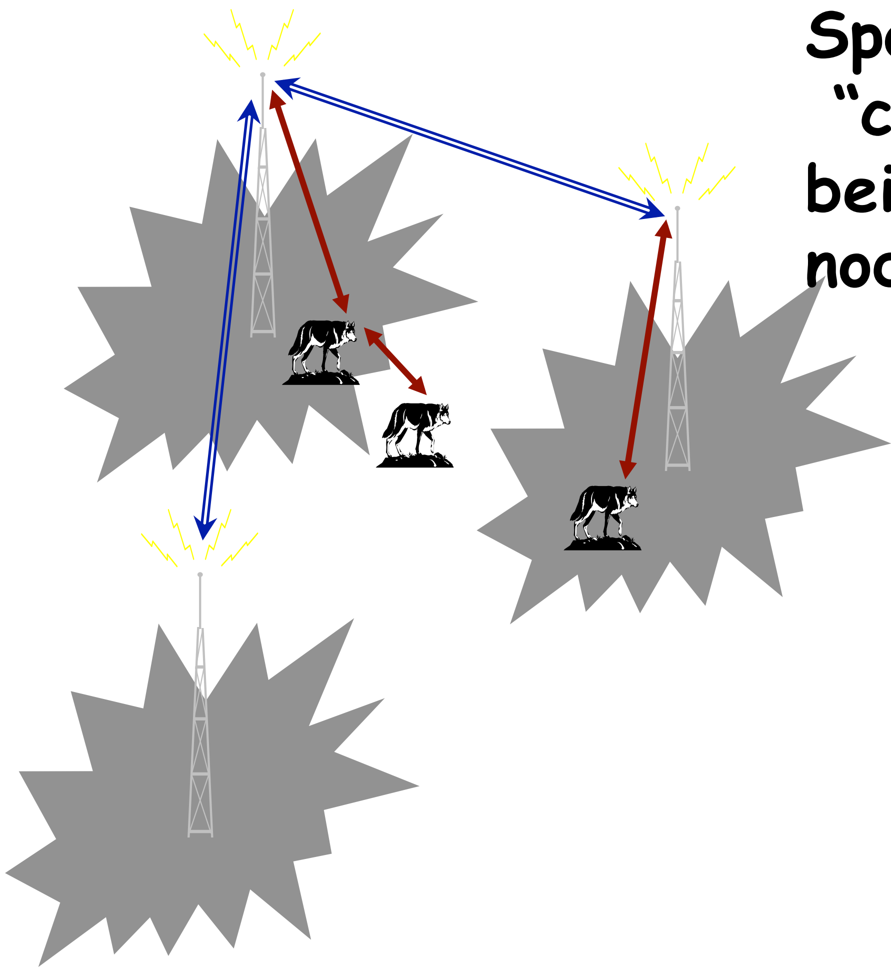
Application Scenario – Wildlife Monitoring

- **ZebraNet**

Do zebras in the African bush have a pattern of migration or do
they just move around in a random fashion across the year?

- A Princeton University project
- Custom tracking collar with GPS (node) is put on the neck of the zebra.
- Nodes record zebra's location and stores in memory.
- Nodes carry the data until meet another node.
- Exchanges data with another zebra when in communication range.
- Mobile base station (MBS) collects data from collars when researchers are in the field.
- MBS is not fixed, rather it moves and is only intermittently available
- Physical presence of the researchers is no longer required at the deployment site in order to collect and publish zebra mobility pattern data.
- Network connectivity is intermittent and opportunistic

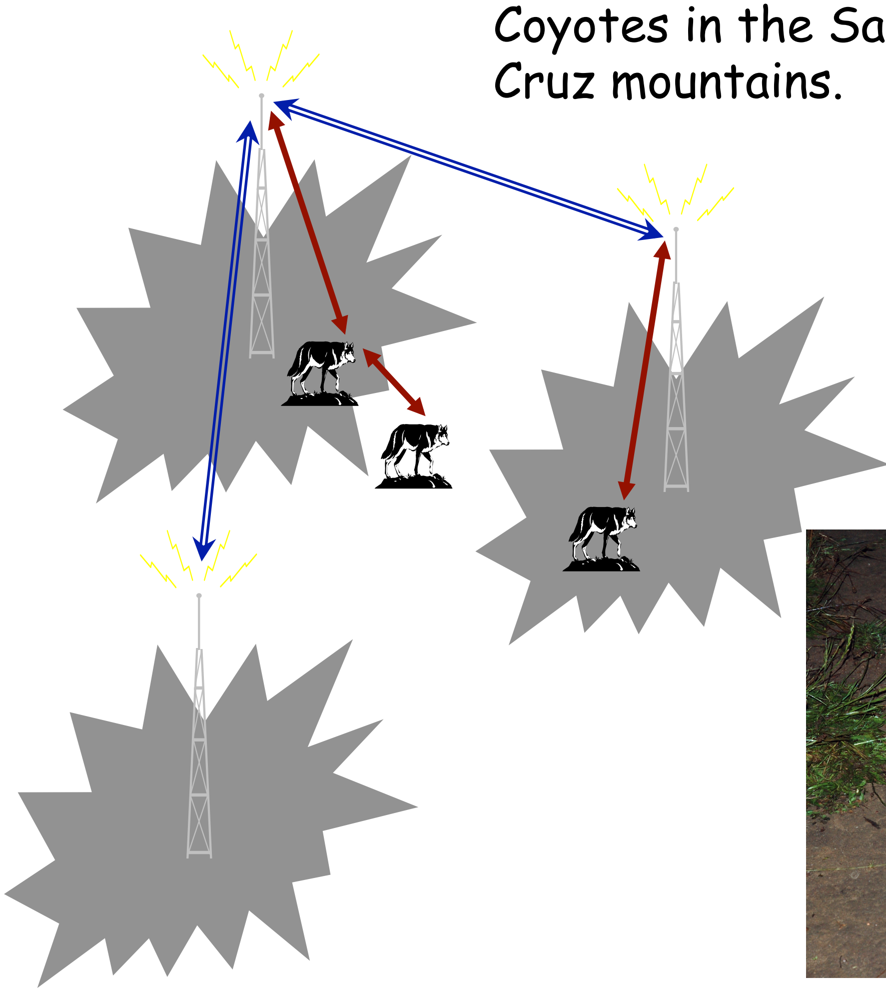
Habitat Monitoring

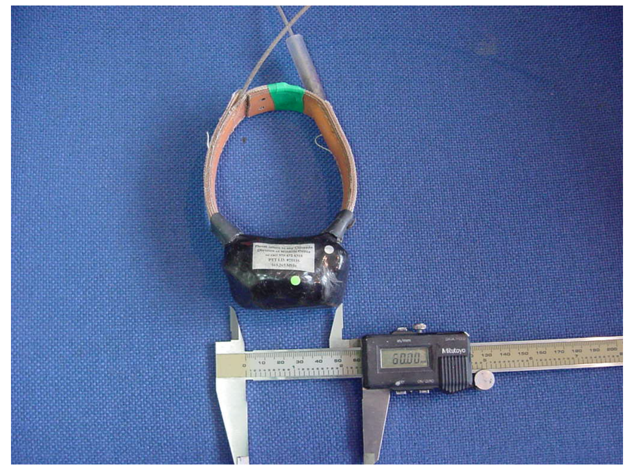


Sporadic connectivity; random "contacts" depending on object being monitored, terrain, nodes, etc.

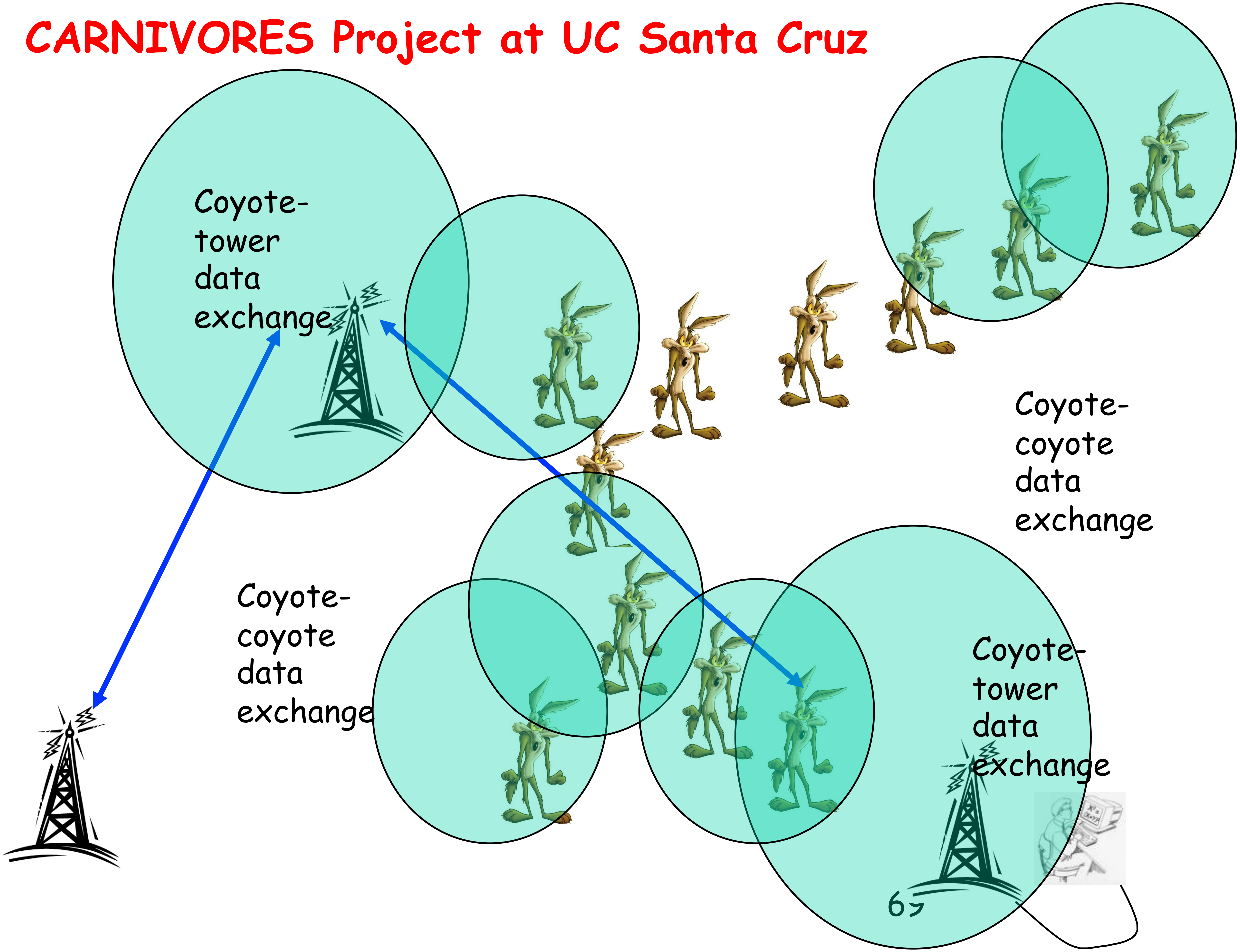
Example: CARNIVORES Project at UC Santa Cruz

Monitoring/tracking Coyotes in the Santa Cruz mountains.





CARNIVORES Project at UC Santa Cruz

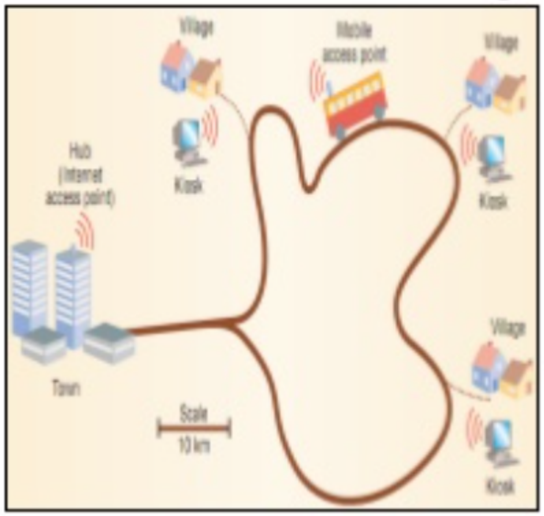


Internet in Remote Regions

Application Scenario – Communication in Rural Villages

- **DakNet**

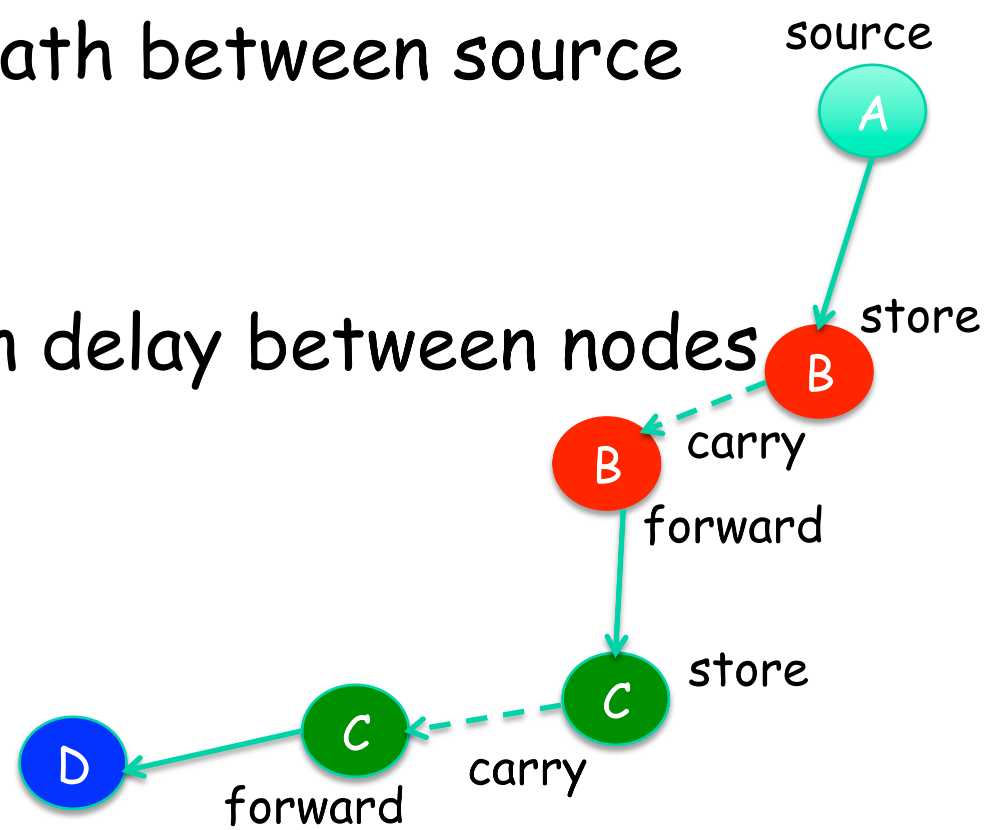
  Goal: Bring Internet connectivity to rural areas



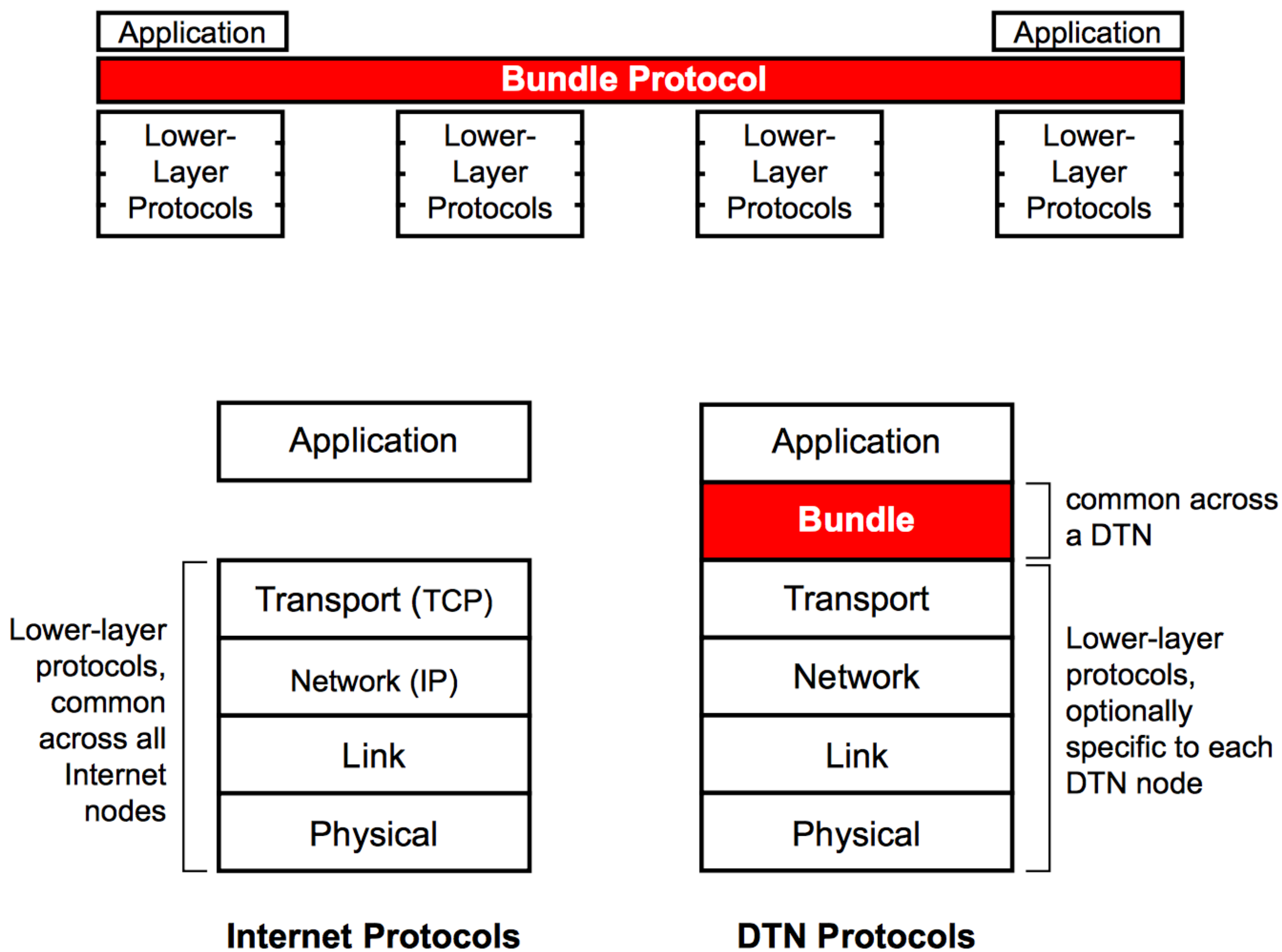
- It is aimed at providing cost-effective connectivity to rural villages in India, where deploying a standard Internet access is not cheap.
- Kiosks are built up in villages and are equipped with digital storage and short-range wireless communications.
- Mobile Access Points (MAPs) mounted on buses, motorcycles, etc., exchange data with the kiosks wirelessly.
- MAPs may also download requested info (news, music, etc.) and bring it to villages.
- Kiosks connectivity
  - Dial-up - slow (28 kbps)
  - Short range communication

Delay- and Disruption Tolerant Networks

- DTN features:
  - Intermittent connectivity
    - No end-to-end path between source and destination
  - Long variable delay
    - Long propagation delay between nodes



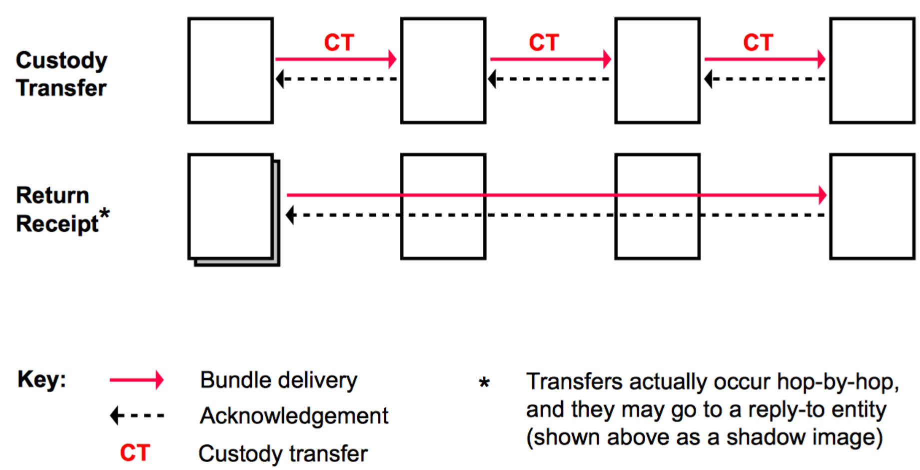
DTN Architecture



IPNSIG, http://www.ipnsig.org

DTN Arquitecture

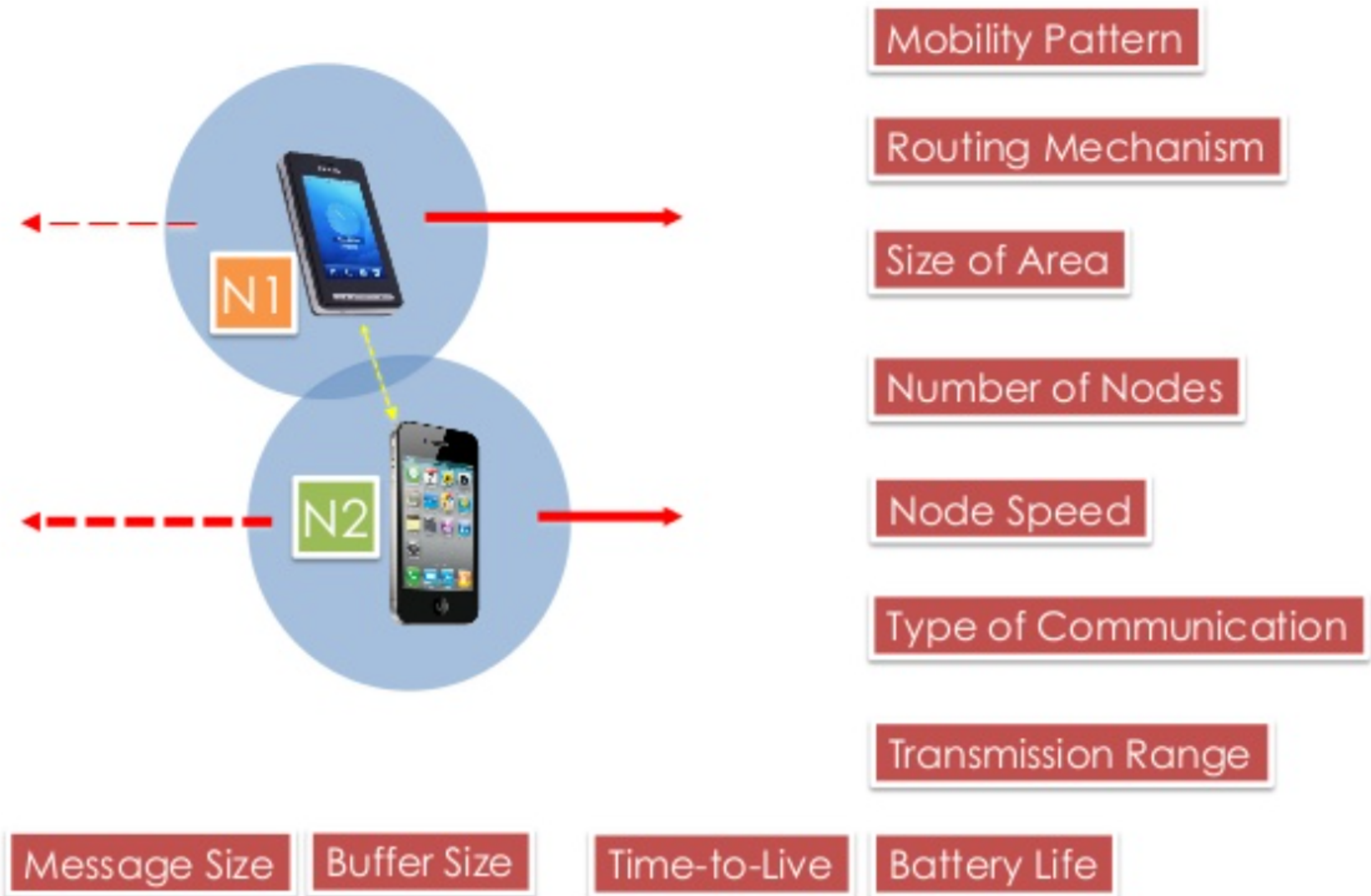
- Types of contact
  - Scheduled
  - Opportunistic
  - Probabilistic
- DTN forwarding techniques
  - Pure epidemic forwarding
    - Spray and wait, Prophet, etc
- "Reliability" concept
  - Custody transfer



IPNSIG, http://www.ipnsig.org

DTN Performance

Factors that impact Performance

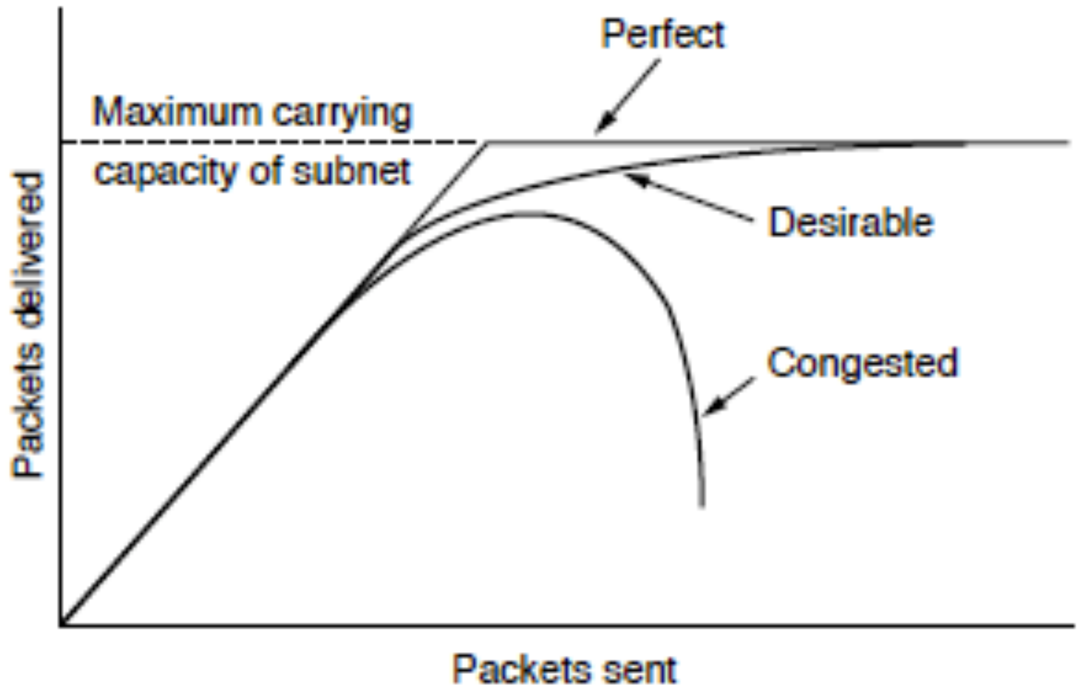


Types of Contacts

- Scheduled contacts
  - E.g. satellite links, message ferry.
  - All info known.
- Probabilistic contacts
  - Statistics about contacts known.
  - E.g. mobility model, or past observation/ prediction.
  - Bus, sensors with random wake-up schedule.
- Opportunistic contacts
  - Not known `a priori.
  - E.g., tourist car that happens to drive by.

DTN Congestion Control

Background
Network Congestion

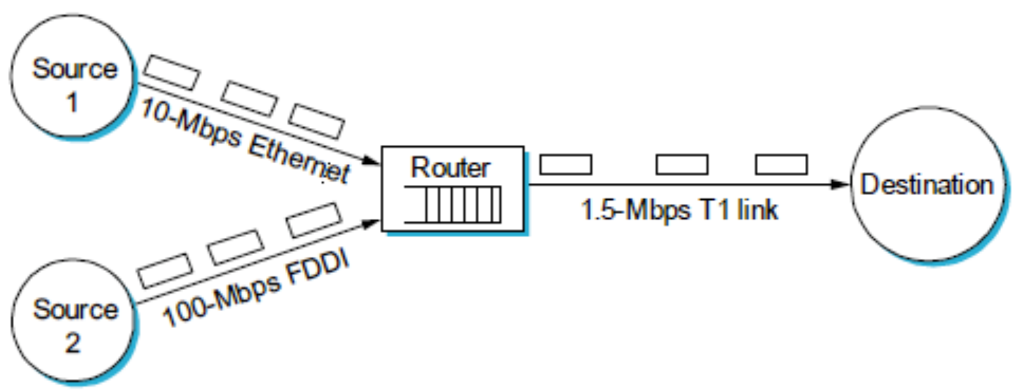


Congestion control is needed to decide how well a network effectively and fairly allocates resources

Congestion control

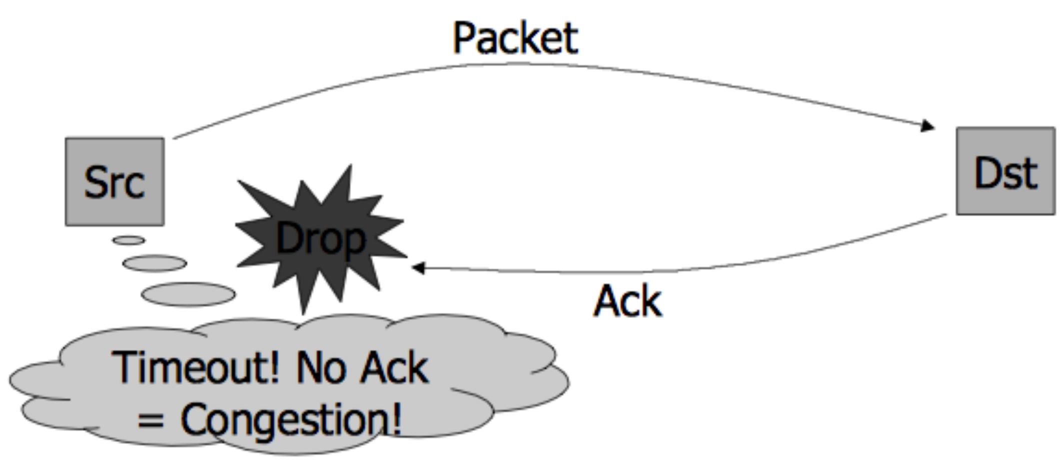
- Efforts made by network nodes and end-points to prevent or respond to overload condition.

Congestion control *paces senders preventing them from overloading the network (e.g., due to network resource unavailability).*



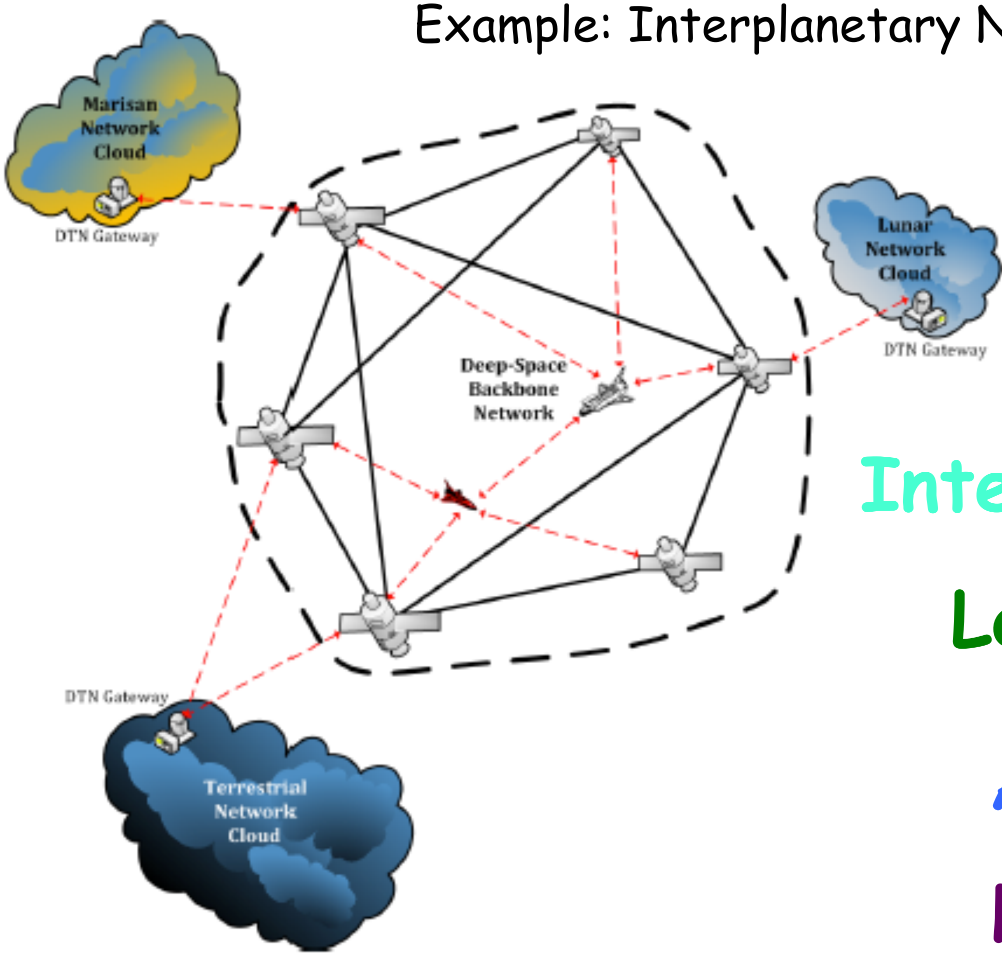
Internet Congestion Control

- Performed by TCP
- End-to-end paradigm
  - End-to-end TCP ACK.



DTN Congestion Control

Example: Interplanetary Network (IPN)



Intermittent Connectivity

Long and variable delay

Asymmetric data rates

High error rates

TCP's end-to-end congestion control mechanisms don't work in DTNs.

DTN Congestion Control

- Several control schemes have been designed for DTN scenarios:
  - Reactive approach
  - Routing protocol dependant
  - Rely on global information
- Can we use these schemes for diverse set of DTN scenarios (e.g., IPN)?

DTN Congestion Control:

- Questions?
  1. Which are good design principles for DTN congestion control mechanisms?
  2. Is there an “universal” congestion control mechanism that will be applicable to all DTN scenarios?

Our approach: Smart-DTN-CC

- Rely on local information
- Proactive and reactive
- Automatically adapts to underlying dynamics

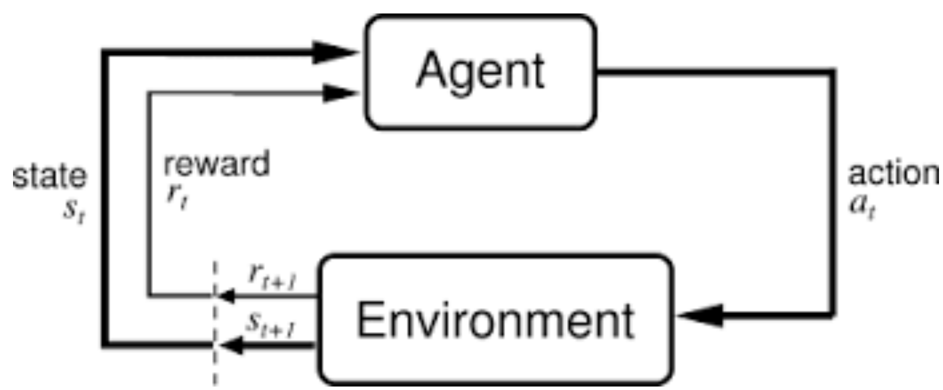
Machine Learning?

"A computer program is said to learn from experience E with respect to some task T and some performance measure P, if its performance on T, as measured by P, improves with experience E." -- Tom Mitchell, Carnegie Mellon University

Reinforcement Learning (RL)?

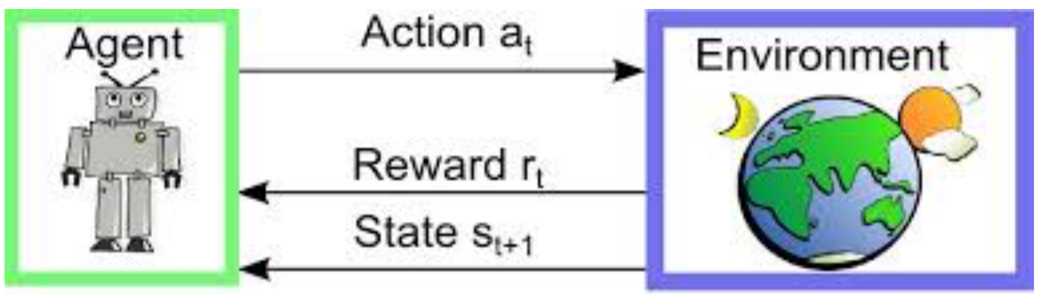
RL: Basic Idea

- Set of states and a set of actions
  - Based on Markov Decision Process
- Select an action
- If action leads to reward, reinforce that action
- If action leads to punishment, avoid that action



RL: Challenges

- Reward/punishment typically delayed
- How do you choose your actions?
  - Exploration vs exploitation

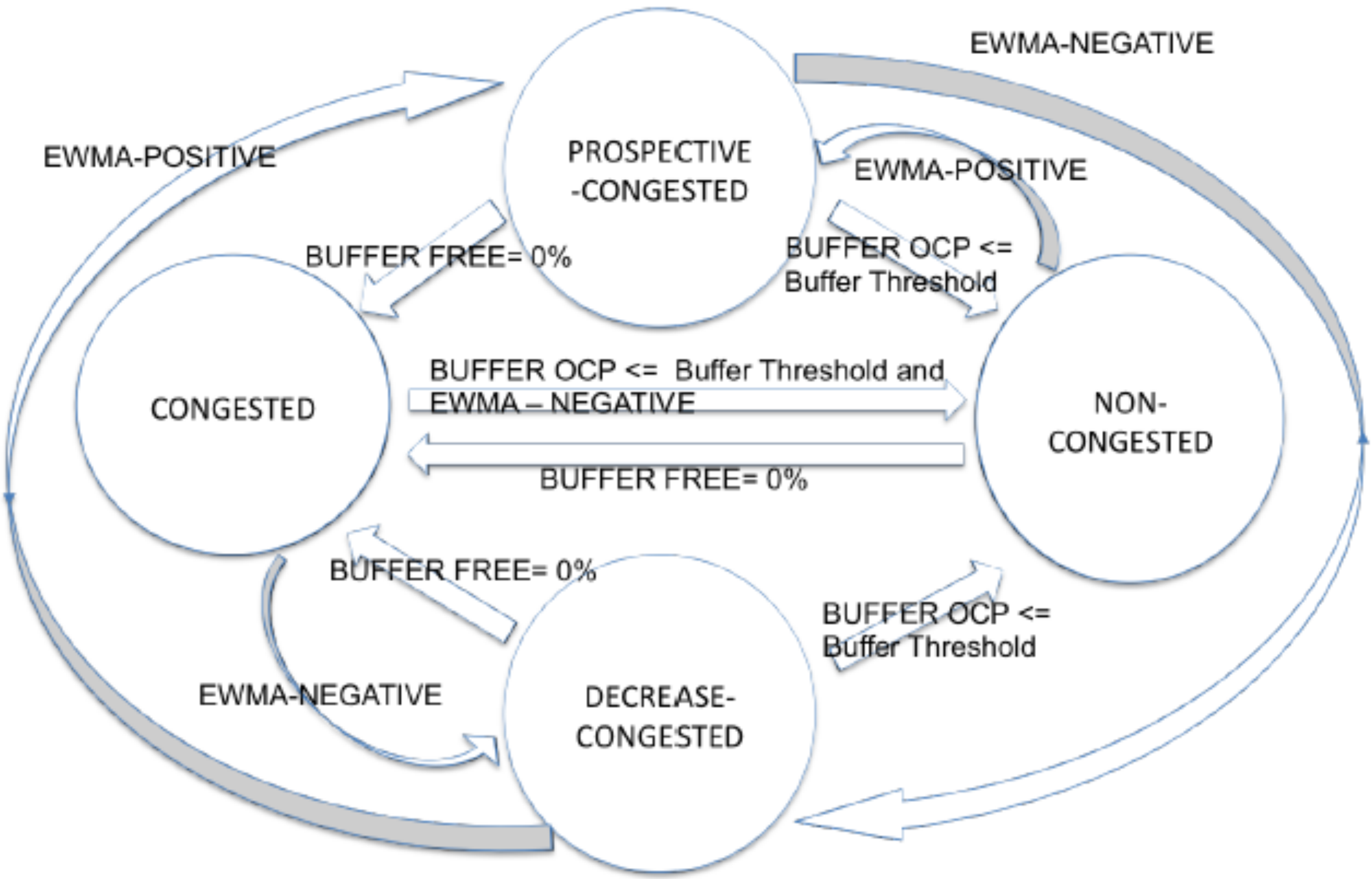


Reinforcement Learning Setup

Why RL in DTN?

- Desired features of DTN congestion control scheme:
  - Provide an autonomous control
    - Agent learns by itself
  - Work independent of the routing protocol
    - The agent tries to know the environment
  - Accommodate diverse applications
    - Terrestrial DTN
    - Interplanetary networks
  - Trigger between different control strategies
    - The agent try to optimize the reward

Our approach: Smart-DTN-CC



Smart-DTN-CC node state machine

Smart-DTN-CC node actions

Actions	States			
	Congested	Prospective-Congested	Decrease-Congested	Non-Congested
Increase message generation period	×	×		
Broadcast CN (Congestion Notification)	×	×		
Discard expired message	×	×	×	×
Discard old message	×	×	×	×
Discard random message	×	×		
Discard message that will expire before next contact arises	×	×		
Discard oldest messages until space available	×			
Migrate messages	×			
Broadcast DCN - Decrease Congestion Notification			×	
Decrease message generation period			×	
Receive messages		×	×	×
Forward messages	×	×	×	×

×: the action can be taken when the node is in the state

Smart-DTN-CC rewards

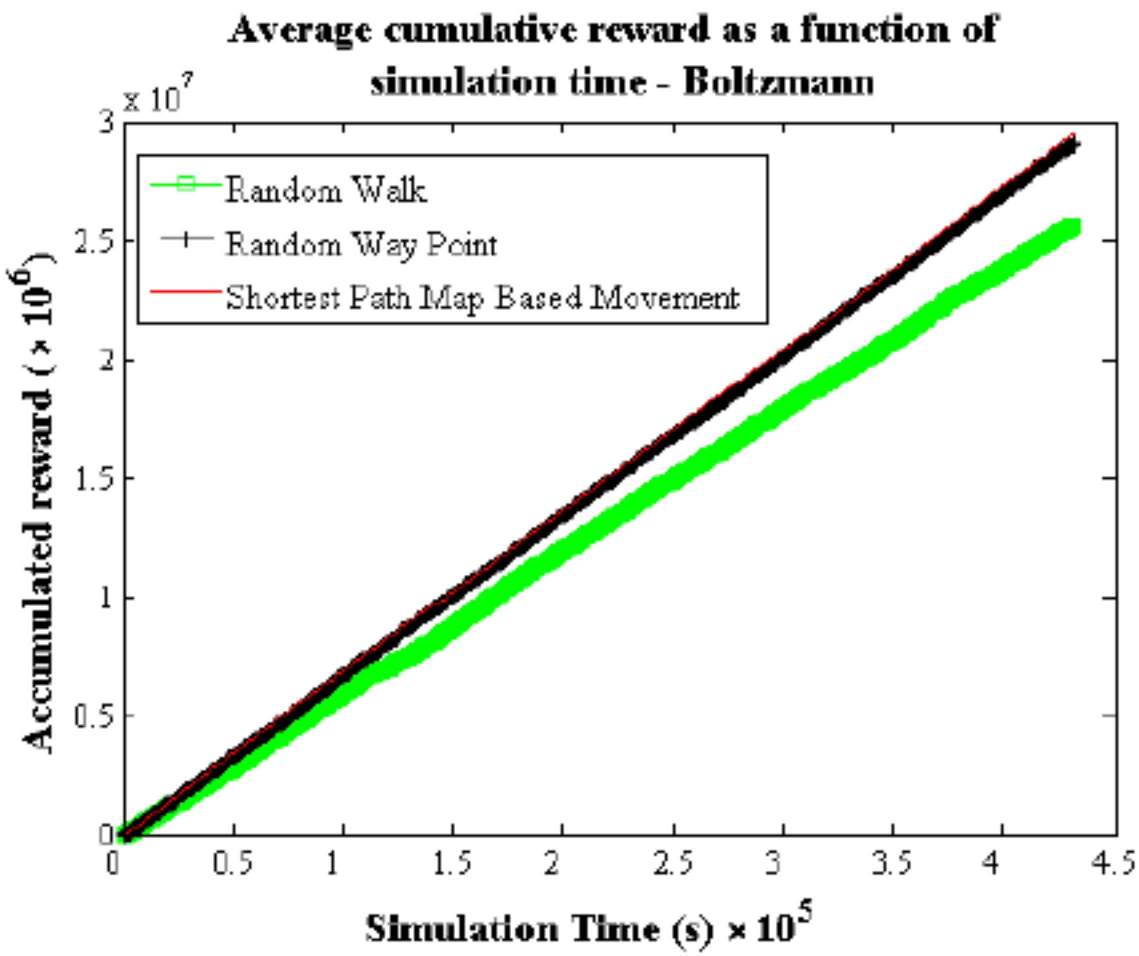
States s	States s'			
	Congested	Non-Congested	Prospective-Congested	Decrease-Congested
Congested	-1	1	-	0.5
Non-Congested	-1	1	-0.5	-
Prospective-Congested	-1	1	-0.5	0.5
Decrease-Congested	-1	1	-0.5	0.5

- : the transition does not exist.

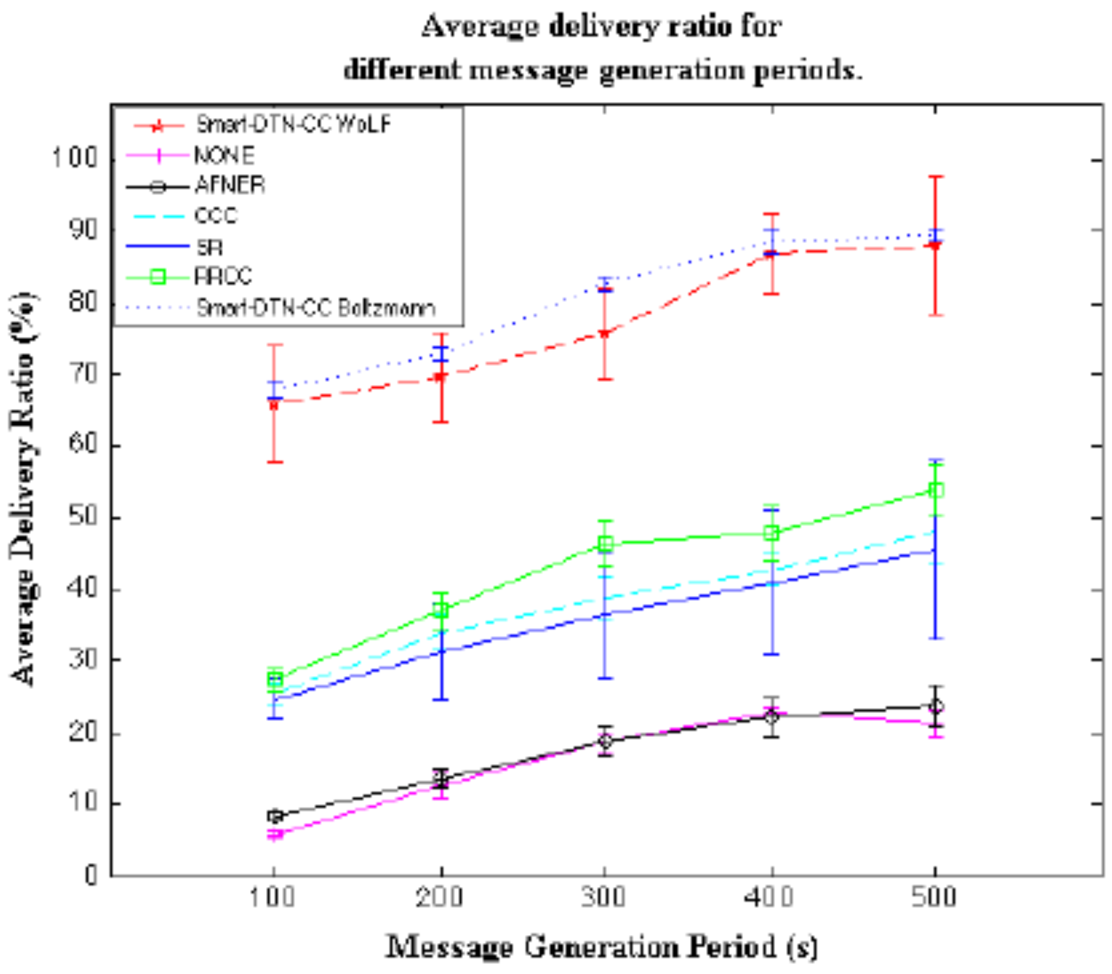
Experimental methodology

- The ONE Simulator
  - http://www.netlab.tkk.fi/tutkimus/dtn/theone/
- Metrics:
  - Average cumulative reward
  - Average delivery ratio
  - Average end-to-end latency

Average cumulative reward



Average delivery ratio



IoT-Based System for Pressure Ulcer Detection and Prevention

With Sam Mansfiled (UCSC PhD student) in collaboration with UC San Francisco

Pressure Ulcers Formation

- Caused from lack of blood circulation because of prolonged pressure, which results in tissue necrosis[1]
- But there are a lot of other risk factors involved[2]

[1] K. Agrawal and N. Chauhan, "Pressure ulcers: Back to the basics," **Indian journal of plastic surgery: official publication of the Association of Plastic Surgeons of India**, vol. 45, no. 2, p. 244, 2012.
[2] F. P. García-Fernández, J. Agreda, J. Verdú, and P. L. Pancorbo-Hidalgo, "A New Theoretical Model for the Development of Pressure Ulcers and Other Dependence-Related Lesions," **Journal of Nursing Scholarship**, vol. 46, no. 1, pp. 28–38, 2014.

Pressure Ulcer Prevalence

- Bed sores occur from the range of 3.3%-53.4%[1]
- Every year almost 2.5 million people develop pressure ulcers and 60,000 deaths are caused directly by them[2]

[1] N. Santamaria **et al.**, "A randomised controlled trial of the effectiveness of soft silicone multi-layered foam dressings in the prevention of sacral and heel pressure ulcers in trauma and critically ill patients: the border trial," **International wound journal**, vol. 12, no. 3, pp. 302–308, 2015.
[2] "Preventing Pressure Ulcers in Hospitals: 1. Are we ready for this change?," Agency for Healthcare Research and Quality, Rockville, 2014. [Online].
[3] C. A. Russo, C. Steiner and W. Spector, Hospitalizations Related to Pressure Ulcers among Adults 18 Years and Older, 2006, Rockville, Maryland: Agency for Healthcare Research and Quality, 2008.

Pressure Ulcer Prevalence

- In 90% of the cases, patients receiving principle treatment for some other medical condition, develop pressure ulcers as a secondary condition[3]

[3] C. A. Russo, C. Steiner and W. Spector, Hospitalizations Related to Pressure Ulcers among Adults 18 Years and Older, 2006, Rockville, Maryland: Agency for Healthcare Research and Quality, 2008.

Pressure Ulcer Prevention and Care

- "This manual repositioning allows parts of a patient's body to recover while the contact forces between their body and the bed are applied elsewhere. However, this system is flawed, only about 66% of patients receive this treatment on a regular basis, most likely due to nursing labor shortages"[1]

C. Lyder, J. Preston, J. Grady, J. Scinto, R. Allman, N. Bergstrom, and G. Rode-heaver, "Quality of Care for Hospitalized Medicare Patients at Risk for Pressure Ulcers," Archives of Internal Medicine, vol. 161, no. 12, pp. 1549–1554, 2001.

Pressure Ulcer Cost

- Estimated cost for treating a bed sore is \$70,000[1]
- The current cost to the US' health care system resulting from PUs is more than \$1.2 billion annually[2]

[1] M. Reddy, S. S. Gill, and P. A. Rochon, "Preventing pressure ulcers: a systematic review," **Jama**, vol. 296, no. 8, pp. 974–984, 2006.
[2] D. Berlowitz, H. Bezerra, G. Brandeis, B. Kader, J. Anderson, "Are weimproving the quality of nursing home care: the case of pressure ulcers,"J Am Geriatr Soc, vol. 48, pp. 59-62, 2000.

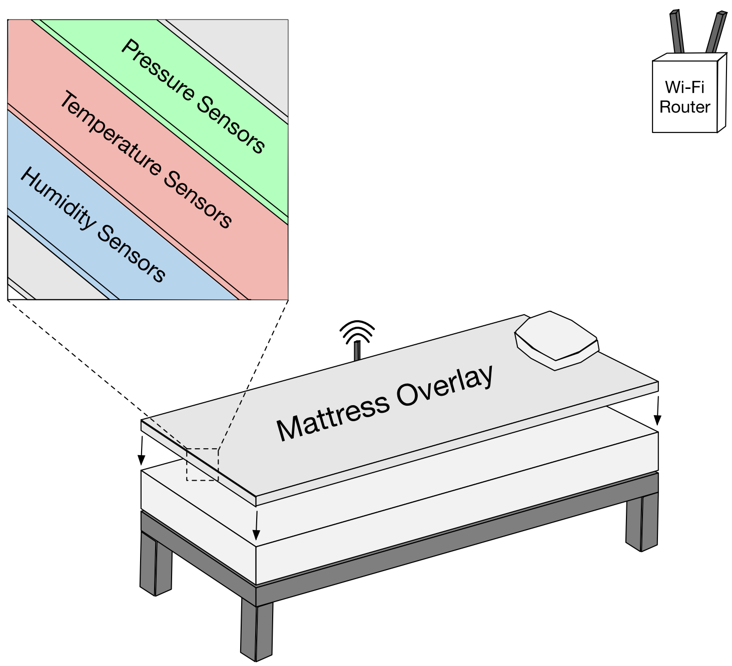
Related Work Sum Up

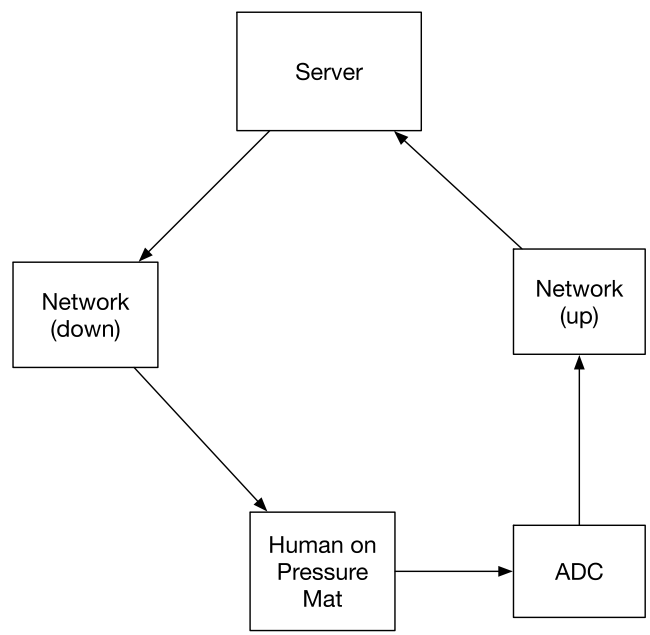
- Lacking in clinical trials or any trials
- Main focus is on pressure redistribution or posture classification
- No study scientifically examining the problem

BSDP: A Research Tool

- Nurse-agnostic, passive monitoring
- Study the formation over time
- Can be used to correlate other sensors
  - i.e. Smartderm could use BSDP as a way to correlate position with the current sensor reading

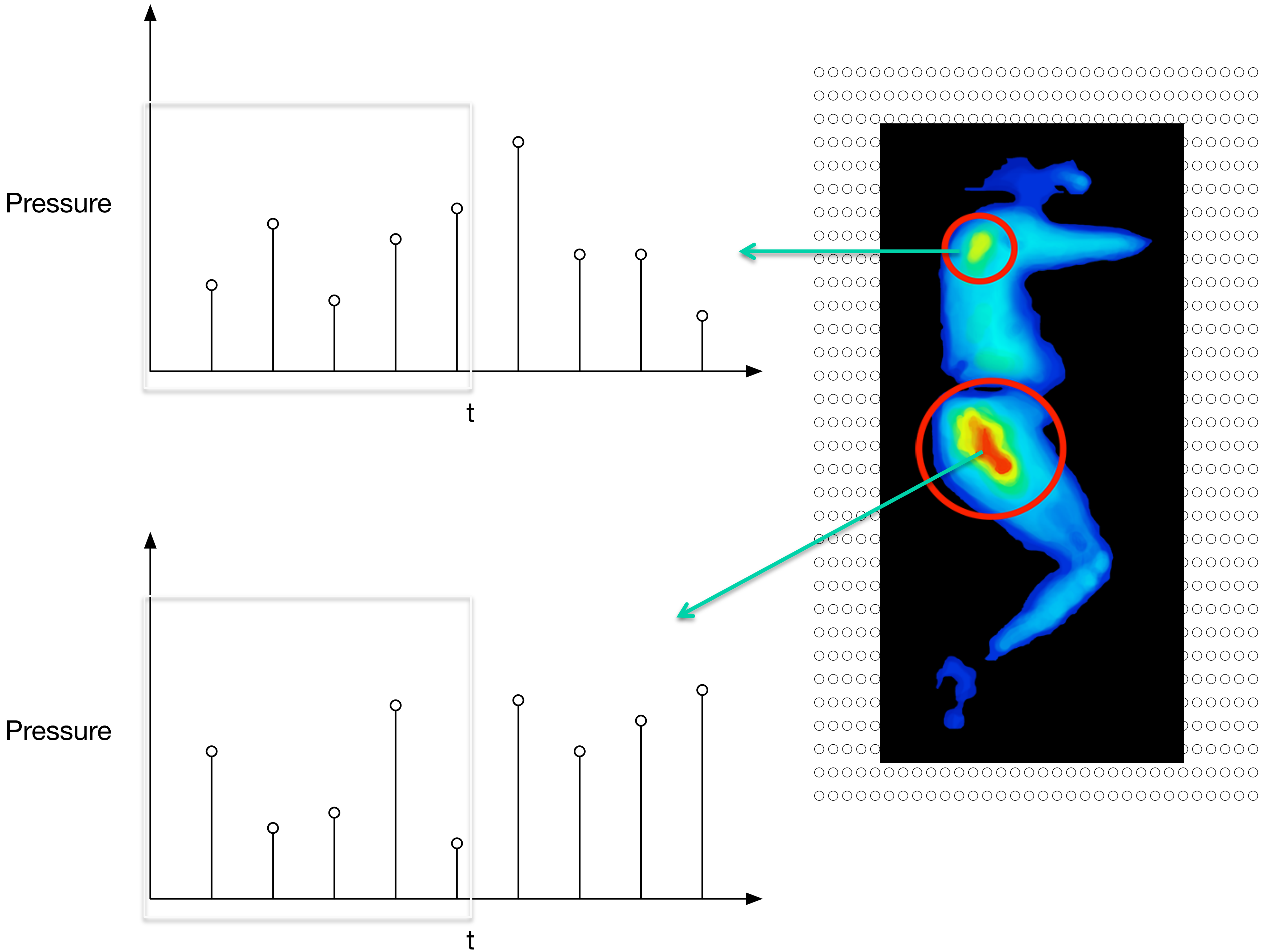
BSDP System Overview





Why Is Our Study Different?

- We want to study the formation of the ulcer
  - As it relates to pressure
  - As it relates to temperature
  - As it relates to humidity, etc.
- We then want to predict the formation
- Use posture detction to make the pressure mat patient centric and then study high risk body parts over time


Pressure
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Pressure
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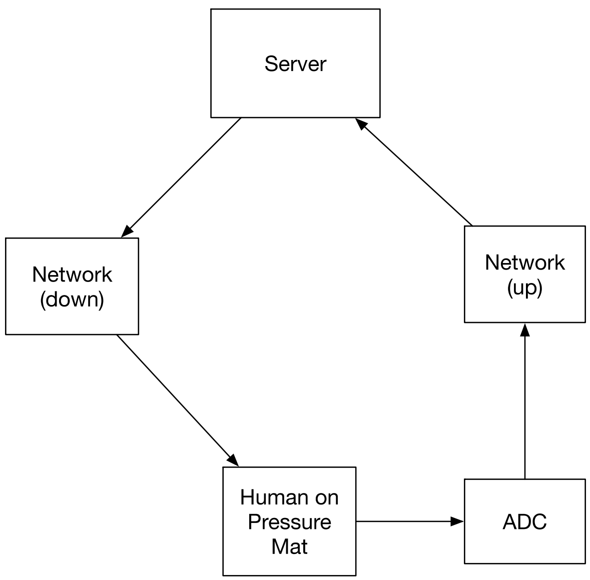
Cyber-Physical Systems (CPS)

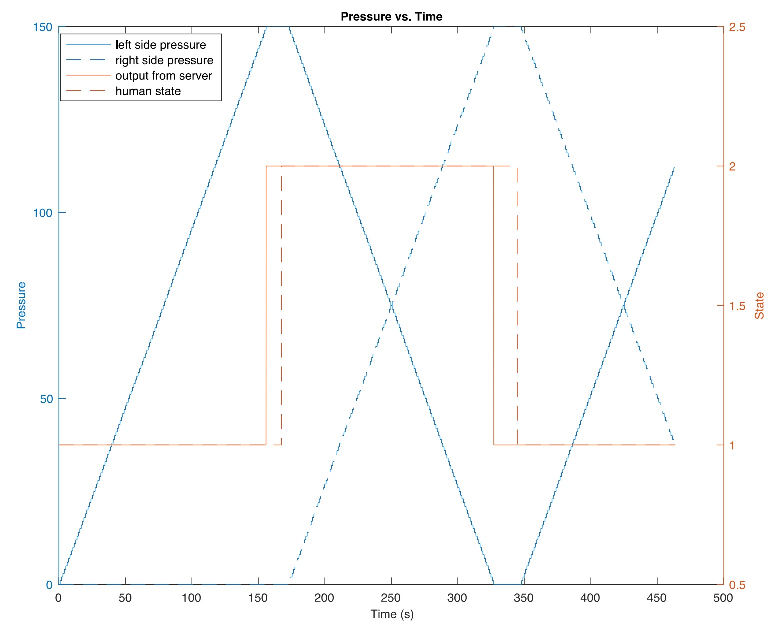
- We currently have a CPS model of the system
- Uses Hybrid Equations Toolbox[1] in Matlab
- Models each component of the system with feedback

[1] https://www.mathworks.com/matlabcentral/fileexchange/41372-hybrid-equations-toolbox-v2-04

CPS Model

- We can use the model to test different algorithms including posture detection





Challenges

- Posture detection (e.g., when pillow is used to support a patient; this can be avoided if also monitoring temperature, as a pillow does not generate heat)
- Getting data is a big challenge
- High risk patients need to be monitored to collect data when a pressure ulcer formed (At this stage healthy patient data is still valuable)

Questions?

- Is studying the pressure as a pressure ulcer forms helpful?
- If we had a system that could predict when a pressure ulcer will form, is this helpful?
- Are there other extrinsic risk factors that should be studied in this manner?
- Are there other applications for a posture detecting pressure mattress? What if it could also detect temperature or humidity?
- Are there known sources of data?

Thank you!

QUESTIONS?