Networked Cyber-Physical Systems (Net-CPS) and the Internet of Things (IoT)

John S. Baras

Institute for Systems Research, University of Maryland, USA
ACCESS Linnaeus Center, Royal Institute of Technology, Sweden
Institute for Advanced Study, Technical University of Munich, Germany

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# Networked Cyber-Physical Systems

## Infrastructure / Communication Networks
- Internet / WWW
- MANET
- Sensor Nets
- Robotic Nets
- Hybrid Nets: Comm, Sensor, Robotic and Human Nets

## Social / Economic Networks
- Social Interactions
- Collaboration
- Social Filtering
- Economic Alliances
- Web-based social systems

## Biological Networks
- Community Epidemic
- Cellular and Sub-cellular
- Neural
- Insects
- Animal Flocks
Net-CPS: Wireless and Networked Embedded Systems
Future “Smart” Homes and Cities

• UI for “Everything”
  – Devices with Computing Capabilities & Interfaces

• Network Communication
  – Devices Connected to Home Network

• Media: Physical to Digital
  – MP3, Netflix, Kindle eBooks, Flickr Photos

• Smart Phones
  – Universal Controller in a Smart Home

• Smart Meters & Grids
  – Demand/Response System for “Power Grid”

• Wireless Medical Devices
  – Portable & Wireless for Real-Time Monitoring
Net-CPS: Wireless Sensor Networks Everywhere

Wireless Sensor Networks (WSN) for infrastructure monitoring

- Environmental systems
- Structural health
- Construction projects
- Energy usage
Net-CPS: Smart Grids

- Conventional: Coal, Nuclear, Oil / Gas, Hydro
- Renewable: Solar, Wind

- Generation
- Transmission
- Distribution
- Utilization

- Smart Grid
- Substation
- Residential/Commercial

- Econometric models
- Low-cost “embedded” energy sensors
- Communications
- Standards for process equipment energy
- Integrated control & energy mgmt.

- ACEEE estimates +2x energy savings
- Able to measure and manage carbon footprint per product line
Net-CPS: Collaborative Autonomy

- Component-based Architectures
- Communication vs Performance Tradeoffs
- Net-HCPS ... human behavior
- Distributed asynchronous
- Fundamental limits
Net-HCPS: Social and Economic Networks over the Web

• We are much more “social” than ever before
  – Online social networks (SNS) permeate our lives
  – Such new lifestyle gives birth to new markets

• Monetize the value of social network
  – Advertising - major source of income for SNS
  – Joining fee, donation etc.
  – …

• Need to know the common features of social networks
CPS, Net-CPS, Net-HCPS

• **CPS**: Technological systems where physical and cyber components are tightly integrated

• **Examples**: smart phones, smart sensors, smart homes, smart cars, smart power grids, smart manufacturing, smart transportation systems, human robotic teams, ...

• **Most of modern CPS are actually networked**: via the Internet or the cloud, or via special logical or physical networks

• **Examples**: modern factories, Industrie 4.0, modern enterprises, heterogeneous wireless networks, sensor networks, social networks over the Internet, Industrial Internet (IIC), the Internet of Things (IoT), ...
With networks new fundamental challenges emerge: network semantics and characteristics

Fundamental challenges on two fronts:
- (a) on the interface between cyber and physical components and their joint design and performance;
- (b) on the implications of the networked interfaces and the collaborative aspects of these systems and their design and performance.

Networked Cyber-Physical Systems (Net-CPS)

Additional challenge: incorporation of humans in Net-HCPS, as system components from start
IoT – Challenges and Opportunities

IoT opens up opportunities across multiple verticals

- Smart City
- HealthCare
- Transportation
- Agriculture
- Connected Car
- Industrial
5G – What is it?
Relation to IoT

Evolution to 5G Networks

High Speed Broadband
- Gigabit Data
- High Band Spectrum

High Performance Networks
- Low Latency
- High Availability

Internet of Things
- Billions of connected devices

Virtualized Infrastructure
- Software-Defined Networks
- Network Function Virtualization (NFV)

Network Slicing
- Customized Services
IoT & 5G: Growth and Characteristics

Massive growth of IoT

<table>
<thead>
<tr>
<th>IoT Market Size</th>
<th>Connected Devices</th>
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<tbody>
<tr>
<td>$7.1T</td>
<td>50B</td>
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<table>
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<tr>
<th>IoT Market Growth</th>
<th>IoT Data Growth</th>
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<tr>
<td>28.1% CAGR</td>
<td>49x</td>
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5G

- **Capacity**: 1000x more traffic, 10-100x more devices
- **Latency**: 1 millisecond
- **Data rates**: 10 Gbit/s @peak
- **Coverage**: 100 Mbit/s wherever

Bandwidth & latency demands
Some IoT Trends

• Analytics automation
• Augmented reality
• Industrial IoT – Smart Factory
• Thing Identity and Management Services
• IoT Governance and Exchange Services
• Edge computing
Outline

• Multiple interacting coevolving multigraphs – three challenges
• Graph Topology Matters
• Networks and Collaboration – Constrained Coalitional Games
• IoT and 5G – the enablers
• SDWN and NFV – SD Architecture for Net-CPS and implications for Net-HCPS
• Conclusions
Multiple Coevolving Multigraphs

- **Multiple Interacting Graphs**
  - *Nodes*: agents, individuals, groups, organizations
  - Directed graphs
  - *Links*: ties, relationships
  - Weights on links: value (strength, significance) of tie
  - Weights on nodes: importance of node (agent)

- **Value directed graphs with weighted nodes**

- **Real-life problems**: Dynamic, time varying graphs, relations, weights, policies
Three Fundamental Challenges

- **Multiple interacting coevolving multigraphs involved**
  - *Collaboration multigraph*: who collaborates with whom and when.
  - *Communication multigraph*: who communicates with whom and when.

- **Effects of connectivity topologies**: Find graph topologies with favorable tradeoff between performance improvement (**benefit**) of collaborative behaviors vs **cost** of collaboration
  - *Small word graphs* achieve such **tradeoff**
  - *Two level algorithm* to provide efficient communication

- **Human group behavior and cognition need different probability models** – the classical Kolmogorov model is **not correct**
  - Probability models over logics (independence friendly logic) and timed structures (constrained event algebras)
  - Logic of projections in Hilbert spaces – not the Boolean of subsets
Distributed Algorithms in Networked Systems and Topologies

• Distributed algorithms are essential
  – Agents communicate with neighbors, share/process information
  – Agents perform local actions
  – Emergence of global behaviors

• Effectiveness of distributed algorithms
  – The speed of convergence
  – Robustness to agent/connection failures
  – Energy/communication efficiency

• Design problem:
  Find graph topologies with favorable tradeoff between performance improvement (benefit) vs cost of collaboration

• Example: Small Word graphs in consensus problems

An Example problem of the Interaction between the Control Graph and the Communication Graph
Expander Graphs

- First defined by Bassalygo and Pinsker -- 1973
- Fast synchronization of a network of oscillators
- Network where any node is “nearby” any other
- Fast ‘diffusion’ of information in a network
- Fast convergence of consensus
- Decide connectivity with smallest memory
- Random walks converge rapidly
- Easy to construct, even in a distributed way (ZigZag graph product)
- Graph \( G \), **Cheeger constant** \( h(G) \)
  - All partitions of \( G \) to \( S \) and \( S^c \),
    \[ h(G) = \min \left( \frac{\text{#edges connecting } S \text{ and } S^c}{\text{#nodes in smallest of } S \text{ and } S^c} \right) \]
- \((k, N, \varepsilon)\) **expander**: \( h(G) > \varepsilon \); sparse but locally well connected \((1 - SLEM(G) \text{ increases as } h(G)^2)\)
Interaction Between Control and Communication Graphs: Agents Learn What is Best for the Team

Example: Maximizing Power Production of a Wind Farm

- Aerodynamic interaction between different turbines is not well understood.
- Need on-line decentralized optimization algorithms to maximize total power production.

Assign individual utility

\[ u_i(t) = \text{power produced by turbine } i \text{ at time } t \]

such that maximizing \( \sum_i u_i(t) \) leads to desirable behavior.
Example: Formation Control of Robotic Swarms

- Deploy a robotic swarm in unknown environment: obstacles, targets etc. have to be discovered.[3]
- The swarm must form a prescribed geometric formation.
- Robots have limited sensing and communication capabilities.

For rendezvous, design individual utility

$$u_i(s_i) = \frac{1}{|\{s_j \in S : ||s_i - s_j|| < r\}|} - \alpha \text{dist}_r(s_i, \text{obstacle}),$$

such that minimizing $\sum_i u_i(t)$ leads to desirable behavior.
The Fundamental Trade-off

• The nodes **gain** from collaborating
• But collaboration has **costs** (e.g. *communications*)
• **Trade-off:** **gain** from collaboration vs **cost** of collaboration

Vector metrics involved typically

**Constrained Coalitional Games**

• **Example 1:** *Network Formation*  -- Effects on Topology
• **Example 2:** *Collaborative robotics, communications*
• **Example 3:** *Web-based social networks and services*
• **Example 4:** *Groups of cancer tumor or virus cells*
Dynamic Coalition Formation

Two linked dynamics
• Trust propagation and Game evolution

\[
\gamma_i(t + 1) = f^i(x_i(t), \gamma_i(t), \gamma_j(t), t_{ij}(t))
\]
\[
t_{ik}(t) = g^i(t_{ij}(t), v_{jk}(t)) \quad \forall k \in N
\]
\[
x_i(t) = h^i(\gamma_i(t), \gamma_j(t))
\]
\[
v_{ij}(t) = p^i(\gamma_j(t), t_{ji}(t))
\]

An example of constrained coalitional games

Stability of dynamic coalition Nash equilibrium
Theorem: \( \forall i \in N_i \) and \( x_i = \sum_{j \in N_i} J_{ij} \), there exists \( \tau_0 \), such that
for reestablishing period \( \tau > \tau_0 \) (Baras-Jiang 05, 09, 10)
- iterated game converges to Nash equilibrium;
- In the Nash equilibrium, all nodes cooperate with all their neighbors.

Compare games with (without) trust mechanism, strategy update:
Consensus with Adversaries

• Solve the problem via detecting adversaries in networks of low connectivity.

• We integrate a trust evaluation mechanism into our consensus algorithm, and propose a two-layer hierarchical framework.
  – Trust is established via headers (aka trusted nodes)
  – The top layer is a super-step running a vectorized consensus algorithm
  – The bottom layer is a sub-step executing our parallel vectorized voting scheme.
  – Information is exchanged between the two layers – they collaborate

• We demonstrate via examples solvable by our approach but not otherwise

• We also derive an upper bound on the number of adversaries that our algorithm can resist in each super-step
Simulations

Adversary outputs constant message. Figure on the left has no trust propagation. Figure on the right has trust propagation.
Conquering Heterogeneity -- NFVI & VIM

NFVI + VIM: Foundations of NFV

Resource Management for NFV Applications

- **NFV Infrastructure (NFVI)** – The physical resources (compute, storage, network) and the virtual instantiations that make up the infrastructure.
- **Virtualized Infrastructure Manager (VIM)** - The VIM manages the NFVI and the serves as a conduit for control-path interaction between VNFs and NFVI.
VIM's role in resource management is more closely tied with the NFVI infrastructure. Similarly SDN Controller is key to resource management of the networking layer (virtual or physical).
NFVI – Not a Monolithic Component

Key Sub-Components Play Important Roles

Strong virtualization layer, with important properties – hardware compatibility, I/O performance, robust and mature virtual capabilities are critical to a strong foundation.
Network Slicing

Network Slicing – 5G Networks
A single network to serve multiple networks

Low Bandwidth
High Bandwidth
High Latency
Low Latency

Cloud Orchestration | Operations Management

VMware vCloud NFV Infrastructure
Service Automation

An NFVI platform to extend innovative service offerings

Service Growth
- VNF On-boarding
- Service Creation
- Service Deployment

Results
- Speed new service delivery
- Ease of deployment
- Automation at scale
Use Case – Virtual CPE
Use Case -- SDWAN

SD-WAN

Cloud Orchestration | Operations Management

SP Data Center
NFV Multi-VNF Ecosystem

vCloud NFV

IT Data Center

Private Network

Public Cloud

(MPLS / EPL)

vSD-WAN Edge

vCloud NFV

vSD-WAN Controller

VMWARE

Public Cloud

4G/LTE
Virtualizing the Network – Network as a Service (NaaS)?
Virtualizing the Network

Final Picture: Datacenter to Cloud

Total Flexibility
- Any Workload
- Any Hypervisor
- Any Orchestration
- Any Datacenter
- Any Network underlay
- Any Combination

Consistent Automation and Total control
Virtualizing the Network

SD-WAN: Over Private IP and Internet

Total Flexibility
- Any Network
- Any Location
- Any Service; L2 or L3
- Any Uplink
- Any X86 Platform
- All combinations

Consistent Automation and Total control

Ericsson
Virtualizing the Network

Final Destination: Automated Networks without Borders

Ericsson
Application Delivery – Network Slicing

Network slicing and application delivery.
Supporting Multiple Virtualizations

Multi-VM Infrastructure

Ericsson
Basic SDWN Architecture

Different functionalities distributed along three planes
Resource Allocation in Virtualized Environments
VEPC - NF PLACEMENT

UE → S-GW → MME → P-GW

50ms

UE → S-GW → MME → P-GW

50ms

UE → S-GW → MME → P-GW

50ms

Cellular core

PDN

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APPROACH

- Approach:
  - Single-stage solver
  - Cellular operator has network-wide view
- Main objective:
  - Load balancing across the cellular core
  - DCs close to eNBs are under heavy load (KLEIN [SOSR 2016])
- Assumptions:
  - Single S-GW and MME per UE (3GPP)

NF placement solvers:
Mixed Integer Linear Programming (MILP) formulation
  ✓ Optimality
  ✗ High time complexity
Linear Programming (LP) formulation
  ✓ Lower time complexity
  ✗ Optimality gap
MULTI-TENANT NETWORK VIRTUALIZATION ENVIRONMENTS
- Sliceable infrastructures (e.g., FI testbeds)
- DCs

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INTER-INP VIRTUAL NETWORK EMBEDDING

Challenges:
- Limited knowledge of substrate topology/resources
- Coordination between tenants tools and InPs
APPROACH

- Bird’s eye view:
  - Two-stage solver
    1. Request Partitioning
      - Abstract view of substrate resources (multiple InPs)
    2. VN Embedding
      - InP has network-wide view of own resources
      - Establishing Interconnection
  - Main objective:
    - Minimize embedding cost
    - Load balancing
SOFTWARE DEFINED CPS ARCHITECTURE
Summary and Conclusions

• Net-CPS model – dynamic multiple multigraphs
• Effects of topology on distributed algorithm performance
• Fundamental tradeoff between the benefit from collaboration and the cost for collaboration – constrained coalitional games
• IoT and 5G – the enablers
• SDWN and NFV key methods to address heterogeneity
• Extending UMD Model-Based Systems Engineering (MBSE) Framework to include Humans
• Challenges
Thank you!

baras@isr.umd.edu
301-405-6606
http://dev-baras.pantheonsite.io/

Questions?