A Layered Protocol Architecture for Scalable Innovation and Identification of Network Economic Synergies in the Internet of Things

Tilman Wolf¹ and Anna Nagurney²

¹Department of Electrical and Computer Engineering
University of Massachusetts Amherst
²Department of Operations and Information Management
University of Massachusetts Amherst

Internet of Things

- Internet of Things (IoT) / cyber-physical systems (CPS)
  - Interaction between physical world and computational world
  - Main components: sensors, computation, actuators

- Our focus: Internet of Things (IoT)
  - Broader view on networked CPS
  - Aim is not on safety-critical / real-time systems
Today’s IoT Architectures

- Internet of Things solves societal problems
  - Many potential application domains
- Existing IoT systems use **stovepipe architectures**
  - Single administrative entity deploys sensors, actuators, computation
- **Shortcomings** of vertical integration
  - Design complexity
  - System cost
  - Limited economy of scale
  - Limited innovation

Vision for Large-Scale Internet of Things

- **Scalability** in IoT
  - **Horizontal integration**
  - Use of sensors and actuators across domains
- Platform for innovative new applications
  - New ideas do not require hardware deployment
- **Technical challenges**
  - Interoperability
  - Economic incentives to participate
  - Security and trust across domains
Contributions

- How to design system architecture for IoT?
  - Put in place principles that enable broad deployment and use
  - Limit constraints to enable novel application in future
- Our paper presents
  - Layered IoT protocol stack as architecture for horizontal integration
  - Exchanges to accommodate different contexts
  - Network economic synergies underlying IoT architecture
- Position paper on fundamental architecture
  - Not a finished implementation
  - Baseline for discussion and future works
  - Evidence from a related ChoiceNet project that these ideas can work

Outline

- Introduction
- Layered Protocol Architecture
  - IoT Stack
  - Example
- Exchanges
  - Network economic synergies
- Experience from related project
  - ChoiceNet
- Conclusions
IoT Architecture

- **Horizontal integration requires many-to-many connections**
  - Interconnection between different, physical or logical IoT components
    - Metcalfe’s law: value increases superlinearly with number of devices
  - Need clear isolation of complexities, definition of functionality and interfaces
- **Inspiration: OSI protocol stack and WWW**
  - TCP/IP sockets enable communication between vastly different devices for many different purposes
  - HTTP/HTML allows for common access to information
- **IoT is not only about communication**
  - Interaction with physical world, computation for control, etc.
- **Abstractions that encompass all IoT activities**
  - Our proposed IoT Protocol Stack

IoT Protocol Stack

[Diagram of the IoT Protocol Stack]

- User layer
- Context layer
- Control layer
- Information stream layer
- Interconnection layer
- Device layer
- Physical layer

User preferences
- Optimization criteria, policies, economics
- IoT control loop
- Network
  - Global Internet
  - Local network
- Global Internet
- Local network
- Global Internet
- Local network

Sensor
- Embedded processor
- Control loop
- Physical sensor
- Embedded processor
- Control loop
- Physical actuator
- Embedded processor
- Control loop
- Physical world

Network
- Data aggregation, format conversion, verification
UMassAmherst

Physical Layer

- Physical layer
  - **Sensors** and **actuators** interacting with physical world
  - Interface:
    - Upward to device layer: raw sensor information, actuator status
    - Downward from device layer: sensor configuration, actuator control

UMassAmherst

Device Layer

- Device layer
  - Translation of **sensor data** and **actuator control** into common formats
  - **Management of resources** (sensors, actuators, device energy, etc.)
  - Interface:
    - Upward to interconnection layer: sensor information in standard format
    - Downward from interconnection layer: actuator control in standard format
  - Local (“real-time”) control loop for sensors and actuators
Interconnection Layer

- Interconnection layer
  - **Communication** and **networking** between IoT devices and computational components of IoT stack
  - Interface:
    - Upward to information stream layer: sensor information from one or more IoT devices
    - Downward from information stream layer: control of actuator(s)

Information Stream Layer

- Information stream layer
  - Coherent **information stream** (transition from data to information)
    - Format conversion, sensor verification, interpolation/extrapolation, etc.
  - Interface:
    - Upward to control layer: aggregated information stream from sensors
    - Downward from control layer: aggregated control decision for actuators
Control Layer

- Control layer
  - "Non-real-time" control loop
    - Sensors -> actuators -> physical world
  - Interface:
    - Upward to context layer: control options of IoT system ("knobs")
    - Downward from context layer: desired IoT behavior ("set point")

Context Layer

- Context layer
  - Goals and constraints of IoT system operation
    - Optimization goal, policy adherence, monetization, etc.
  - Interface:
    - Upward to user layer: available options for user input
    - Downward from user layer: user preferences
User Layer

- **User layer**
  - Interactions with user (or user application)
  - Interactions that require "human in the loop"
    - System operation tradeoffs (e.g., performance vs. efficiency)
    - Decisions relating to security, privacy, money, etc.

---

Example: Home Automation

- **User layer**
  - Input of tradeoffs between comfort and cost
- **Context layer**
  - Optimization to minimize energy consumption based on weather forecast
- **Control layer**
  - Control mechanism to turn on A/C based on spot price of electricity
- **Information stream layer**
  - Coherent stream of (spatially and temporally diverse) sensor readings
  - Current price of electricity in a spot market, local weather forecasts, etc.
- **Interconnection layer**
  - X10, ZigBee, UPB, or WiFi Network
- **Device layer**
  - Embedded systems that read sensor data
  - Control boards that drive analog inputs to actuators
- **Physical layer**: sensors and actuators
  - Sensors: temperature sensors, occupancy sensor, light switches, ...
  - Actuators: heating control, A/C control, lights, shades, ...
Example: Home Automation

- **Opportunities for horizontal integration**
  - Occupancy sensor can be reused
    - Home security application
  - Anonymized information streams can be used by utilities for planning
    - Temperature information stream
    - User inputs
  - Smart GPS or traffic management application can provide inputs
    - Change of control settings based on expected arrival of user(s)
  - Health care application may override control settings
    - Setting of temperature to healthier, but more expensive setting

- **Need to deal with conflicting objectives and policies**
  - “IoT Exchanges”

How to Implement IoT Stack?

- **Interfaces**
  - Some convenient interfaces exist
    - E.g., sockets in interconnection layer
    - E.g., abstractions for information streams (web services, sensor nets)

- **Systems for implementation**
  - Physical, device, and interconnection layer on embedded systems
  - Interconnection, information stream, control, context, and user layer on private or public cloud infrastructure

- **Resource management**
  - Many-to-many relationship between components and layers
    - Sensor streams can often be replicated
    - Actuator control may need to be multiplexed
Related Work

- **Common interfaces** for IoT
  - Commercial solutions: e.g., Apple HomeKit
  - W3C Web of Things (WoT) interest group:
    - Standardization of IoT component description, interfaces, discovery and provisioning, and security, privacy, and resilience
  - Our work adds overarching architecture

- **IoTDI 2016**: IoT architectures are on many people’s mind
  - “Enabling Synergy in IoT - Platform to Service and Beyond” (Gabe Fierro)
    - Similar goals with specification of a specific ecosystem
    - Our focus is on interfaces and enabling diversity
  - “World of Empowered IoT Users” (Roy Campbell)
    - User control of data is important
    - We achieve similar goals with IoT exchanges (but need to trust third party)
  - “What could possibly go wrong?” (Jon Crowcroft)
    - We can “create value by connecting across silos”

Outline

- Introduction
- Layered Protocol Architecture
  - IoT Stack
  - Example
- **Exchanges**
  - Network economic synergies
- Experience from related project
  - ChoiceNet
- Conclusions
IoT Exchanges

- IoT stack enables connections between components
  - Common interfaces allow any-to-any connection
  - When should such connections be allowed?
- Many contexts for “correct” operation
  - Intent, policies, economics, privacy, security, compliance, etc.
  - Building all these considerations into all layers is difficult
- Mechanism to realize context as needed: IoT Exchanges
  - Computational entities that adapt sensor data and control commands
- Example Exchanges:
  - Privacy exchange: removes identifiable information, aggregates, etc.
  - Economic exchange (“marketplace”): offers sensor data, actuator access for sale

Usage Scenario with Exchanges

- Exchanges realize users’ intent of how to participate in IoT
  - User can set preferences in privacy exchange, price in marketplace
IoT Marketplace

- Key to **incentivizing participation** in horizontal integration
  - Economic rewards for sharing sensor data and actuator access
- Users can offer **sensor data** or **actuator control for sale**
  - Prices for IoT resources can be set by users
  - **Market forces** drive toward equilibrium
- Similar mechanism are already used in Internet, but implicitly
  - Personal data is “sold” in return for service (e.g., search with ads)
- Explicit representation of market allows users to reason better
  - May provide easy solutions to some difficult technical problems
    - E.g., “How much is it worth for me to sell my personal information?”
- Multiple marketplaces can exist
  - IoT resources can be offered in multiple marketplaces

Network Economic Synergies

- **Economic model** for vertical integration:
  - Representation of sensing, computation, and actuation
  - Interactions only within one application domain
- **Optimization** of economic network
  - Links incur costs
  - Optimization of each application separately
Network Economic Synergies

- Economic model for horizontal integration
  - Cross-connections between applications possible
  - Sensor data and actuators can be shared
- Network model optimization
  - Optimization across application
    - Optimization through cost-minimization
    - Centralized decision making
  - **Lower cost** possible
- More details in paper
  - Intermediate models
  - Decentralized decision-making and profit-maximization

Outline

- Introduction
- Layered Protocol Architecture
  - IoT Stack
  - Example
- Exchanges
  - Network economic synergies
- **Experience from related project**
  - ChoiceNet
- Conclusions
ChoiceNet: Economy Plane for Internet

- “Horizontal integration” across network services
- Main idea: apply economic principles to network
  - Network services are offered and sold
  - Contracts are established to buy service
  - Market forces can shape development of network economy
- In our case: create market-based competition
  - Forces increase in quality of offerings
  - Forces lower prices for customers
- Economy plane implements these principles
  - Services are first-class objects in Economy Plane
  - Contracts are mechanisms for interaction in Economy Plane
  - Marketplace is place where interactions take place

Vision: Movie Streaming Example

- Choices for movie streaming
  - Technical choices:
    - Different connections, transport, caching, etc.
  - Economic choices:
    - Pay more or less for a particular video experience
    - Technical choices are packaged and sold as experiences
- End-user interactions with ChoiceNet
  - Select, pay for, and expect a certain experience
- ChoiceNet infrastructure
  - Identify choices, compose suitable offering
  - Distribute money among providers
  - Verify performance
Movie Streaming Example

- Separate flow of money and data
  - User pays video service provider (e.g., Netflix)

Movie Streaming Example

- New services possible without owning physical infrastructure
  - Developer provides cached video service
ChoiceNet Prototype

- Operation from **perspective of end-user**

```bash
wget http://10.10.1.1:8080/sample.npf
```

![Image of a webpage with a PayPal checkout interface]
ChoiceNet Prototype

- Throughput is roughly 1 Mbps

Throughput test:

```
--2014-10-23 21:15:00 -- (try:14) http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

Connecting to 10.10.1.1:8080... connected.
HTTP request sent, awaiting response... 200 OK
Length: 7356259 (7.0M) [video/mp4]
Saving to: 'sample.mp4'
4% [>=] 3,642,657 116K/s ETA 45s
```
ChoiceNet Prototype

- **Throughput is roughly 10 Mbps**

![Throughput Image]

Multi-Criteria Marketplace Search

- **How to find resource choices?**

  - **Multiple criteria** for each link or path
    - Bandwidth, delay, cost, reliability, etc.
  
  - Many existing algorithms **weigh criteria a priori**
    - Does not work if customers preferences are unknown

  - **A posteriori weighting** requires finding of all paths
    - Only **Pareto-optimal set** of paths is interesting
Multi-Criteria Marketplace Search

- **ParetoBFS algorithm**
  - Breadth-first search
  - Pruning of non-optimal partial paths on each node
  - Pruning reduces exponential growth in complexity
    - Still maintains all path necessary to find complete Pareto-optimal set
  - Algorithm can **scale** to very large networks

Simulation of Competition

- Innovation gives **competitive advantage** to Provider 4
Simulation of Competition

- Innovation gives **competitive advantage** to Provider 4

Outline

- Introduction
- Layered Protocol Architecture
  - IoT Stack
  - Example
- Exchanges
  - Network economic synergies
- Experience from related project
  - ChoiceNet
- **Conclusions**
Summary and Conclusion

- **IoT protocol stack** for horizontal integration
  - Layered stack with interfaces that allow many-to-many connections
  - Exchanges to implement different contexts
  - Economic marketplace can help to incentivize and optimize
  - ChoiceNet implements similar ideas for network services

- Impact of (our or other’s) common IoT architecture
  - Scale and ubiquity of IoT
  - Innovation of new IoT applications
  - Participation of individuals in “IoT economy”

Thank you!

Tilman Wolf
wolf@umass.edu
http://www.ecs.umass.edu/ece/wolf/