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

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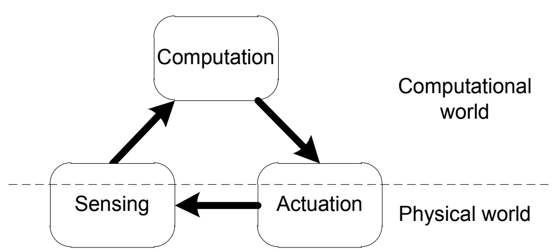
Internet of Things

- 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

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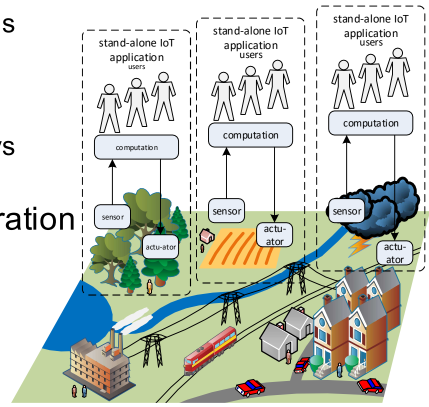
Today's IoT Architectures

- 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



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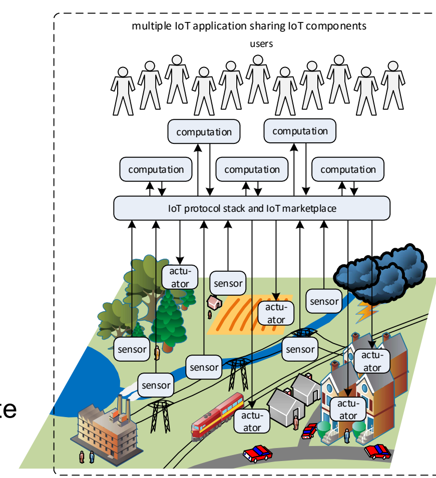
Vision for Large-Scale Internet of Things

- **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



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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

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Outline

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

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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

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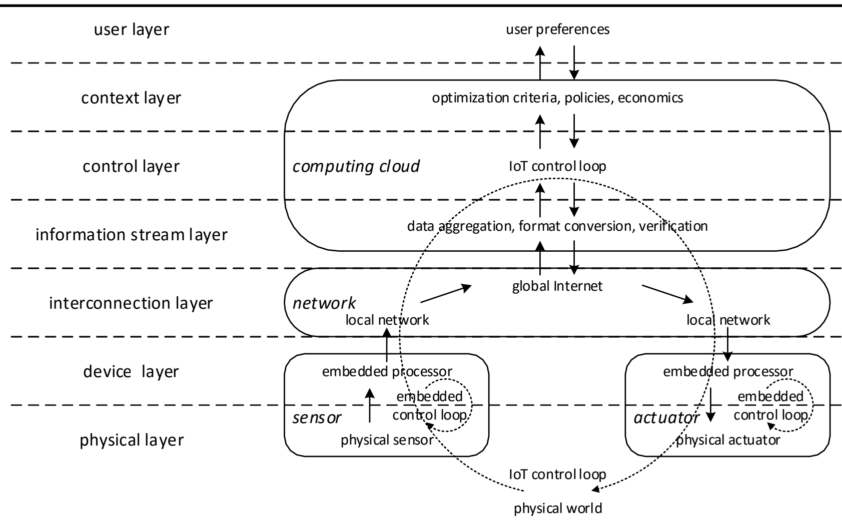
IoT Protocol Stack



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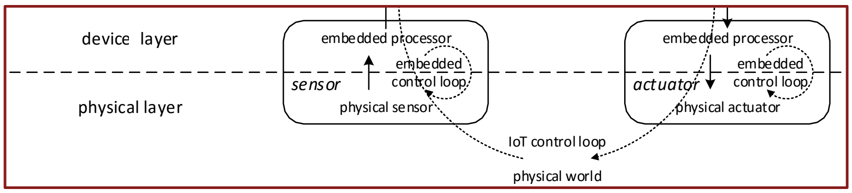
Physical Layer

- 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



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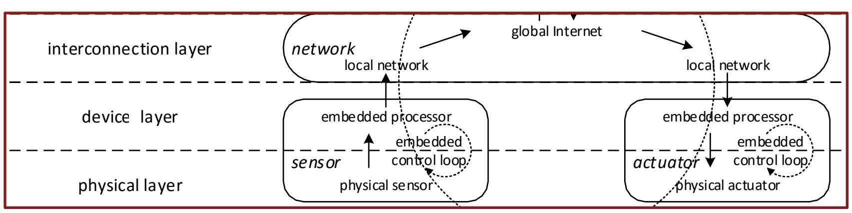
Device Layer

- 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



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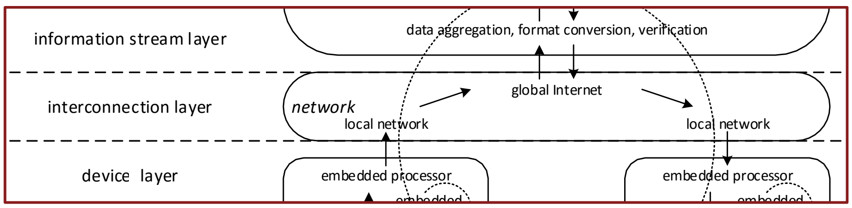
Interconnection Layer

- 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)



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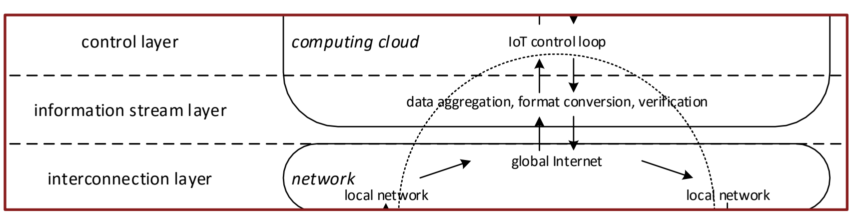
Information Stream Layer

- 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



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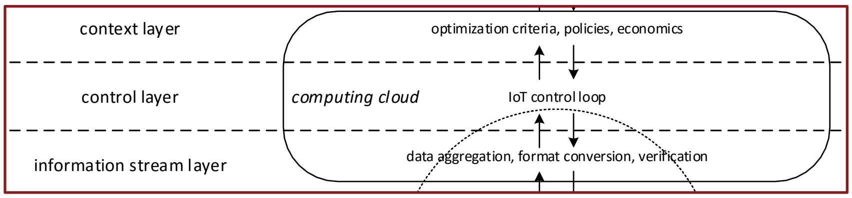
Control Layer

- 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”)



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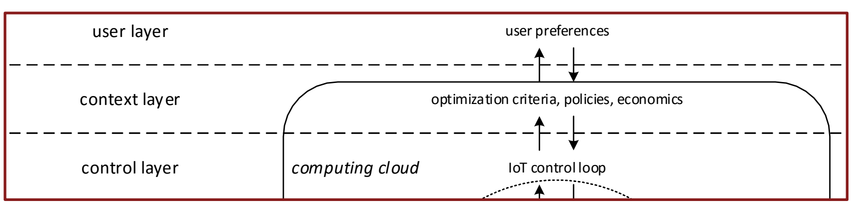
Context Layer

- 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



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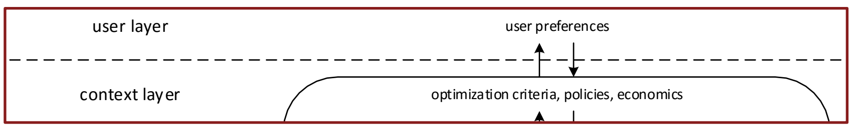
User Layer

- 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.



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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"

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- Introduction
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- **Exchanges**
  - **Network economic synergies**
- Experience from related project
  - ChoiceNet
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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 adapts sensor data and control commands
- Example Exchanges:
  - Privacy exchange: removes identifiable information, aggregates, etc.
  - Economic exchange ("marketplace"): offers sensor data, actuator access for sale

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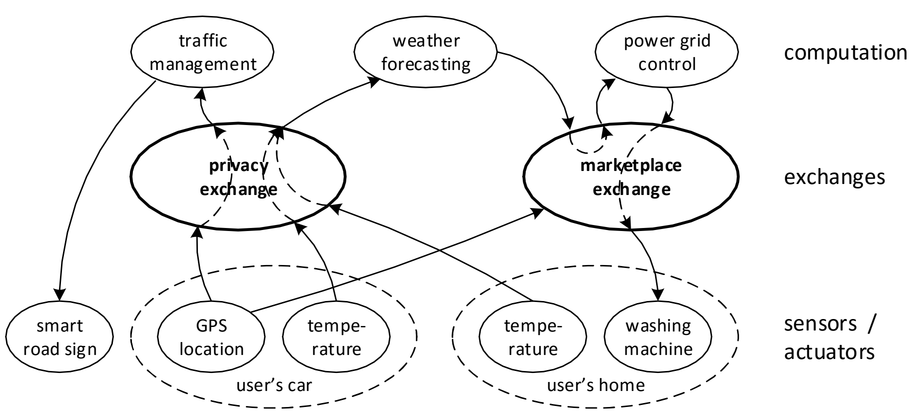
Usage Scenario with Exchanges

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



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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

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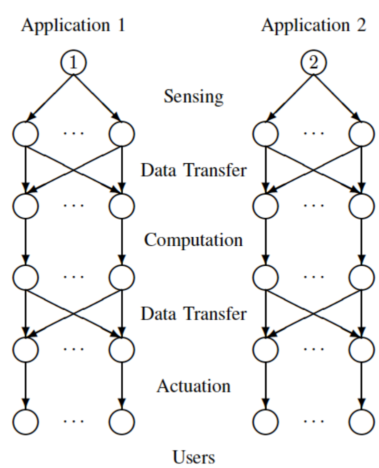
Network Economic Synergies

- **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



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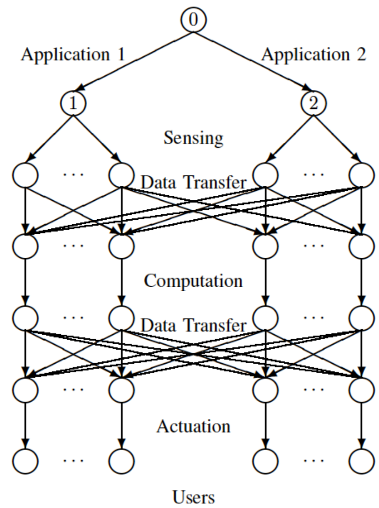
Network Economic Synergies

- 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**



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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

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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

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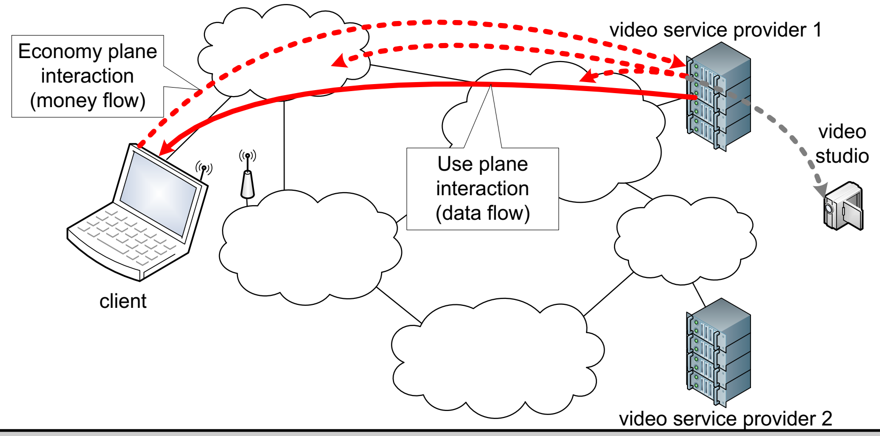
Movie Streaming Example

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



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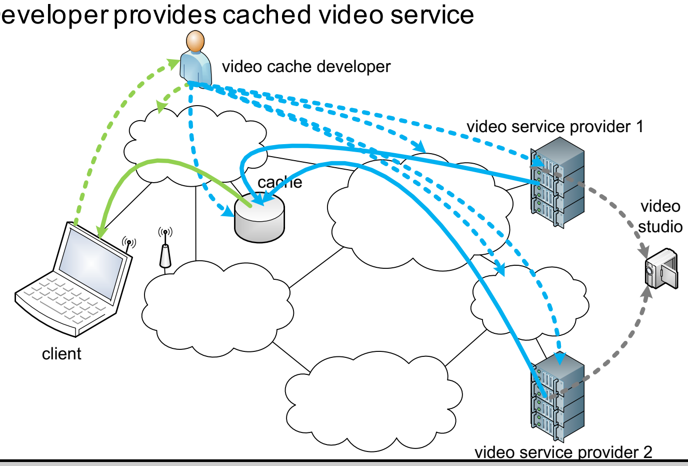
Movie Streaming Example

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



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ChoiceNet Prototype

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

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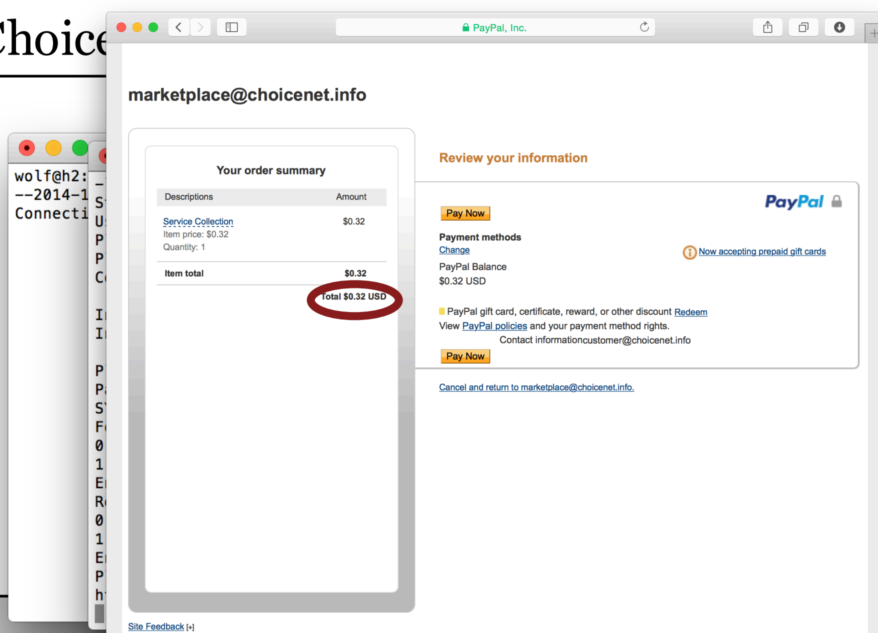
Choice



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ChoiceNet Prototype

- Throughput is roughly **1 Mbps**

```
wolf — wolf@h2: ~ — ssh — 80×24

--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.

--2014-10-23 21:16:13--  (try:15)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

--2014-10-23 21:17:26--  (try:16)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

--2014-10-23 21:18:39--  (try:17)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

--2014-10-23 21:19:52--  (try:18)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... connected.
HTTP request sent, awaiting response... 200 OK
Length: 73516259 (70M) [video/mp4]
Saving to: `sample.mp4'

 4% [>                                  ] 3,642,672   116K/s  eta 9m 47s
```

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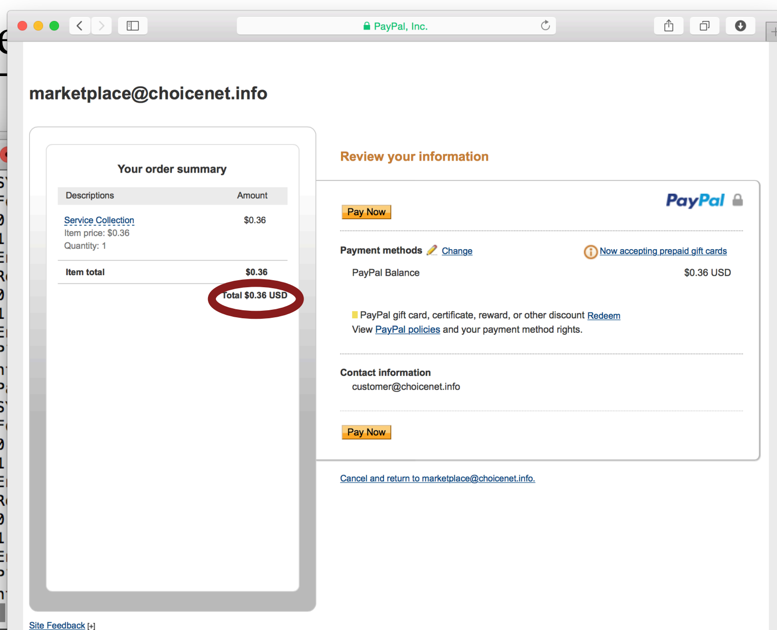
Choice



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ChoiceNet Prototype

- Throughput is roughly **10 Mbps**

```
wolf — wolf@h2: ~ — ssh — 80×24

--2014-10-23 21:38:32--  (try:13)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

--2014-10-23 21:39:45--  (try:14)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

--2014-10-23 21:40:58--  (try:15)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

--2014-10-23 21:42:11--  (try:16)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... failed: Connection timed out.
Retrying.

--2014-10-23 21:43:24--  (try:17)  http://10.10.1.1:8080/sample.mp4
Connecting to 10.10.1.1:8080... connected.
HTTP request sent, awaiting response... 200 OK
Length: 73516259 (70M) [video/mp4]
Saving to: `sample.mp4.1'

31% [===========>                        ] 23,193,8[illegible]1  1.14M/s  e[illegible]a 43s
```

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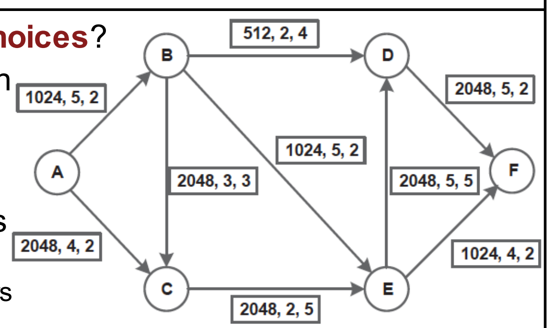
Multi-Criteria Marketplace Search

- 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



Path list at node F:

p_1 =(A,B,D,F): 512, 12, 8
p_2 =(A,C,E,F): 1024, 10, 9
p_3 =(A,B,E,F): 1024, 14, 6
p_4 =(A,C,E,D,F): 2048, 16, 14
} Pareto-optimal path.

p_5 =(A,B,E,D,F): 1024, 20, 11
p_6 =(A,B,C,E,F): 1024, 14, 12
p_7 =(A,B,C,E,D,F):1024, 20, 17
} Not Pareto-optimal and discarded.

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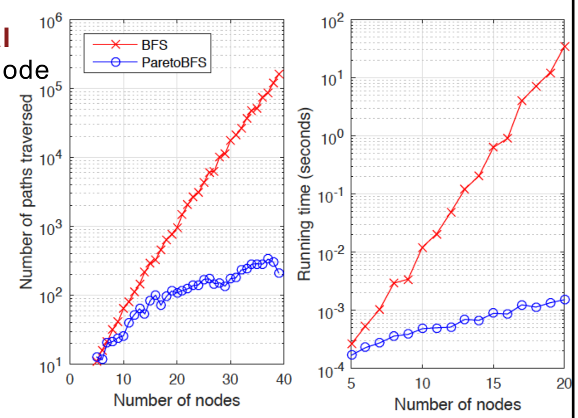
Multi-Criteria Marketplace Search

- **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



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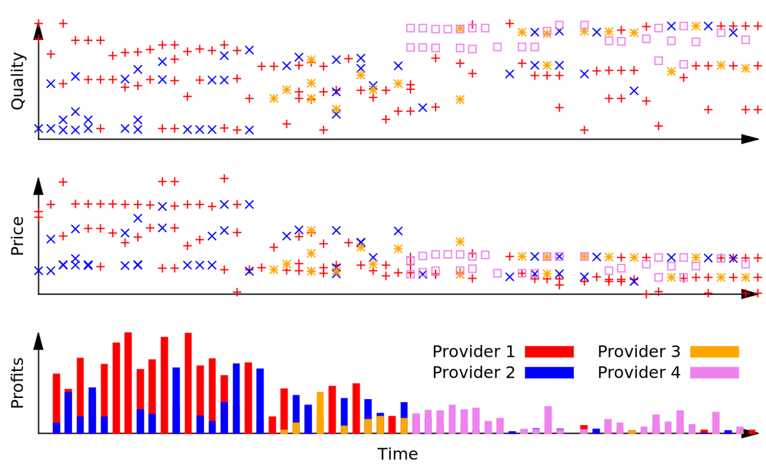
Simulation of Competition

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



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Simulation of Competition

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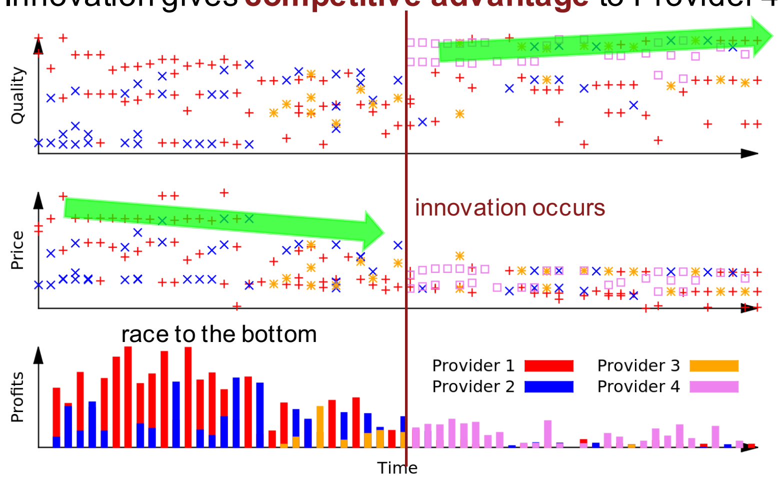

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Summary and Conclusion

- **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"

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Thank you!

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