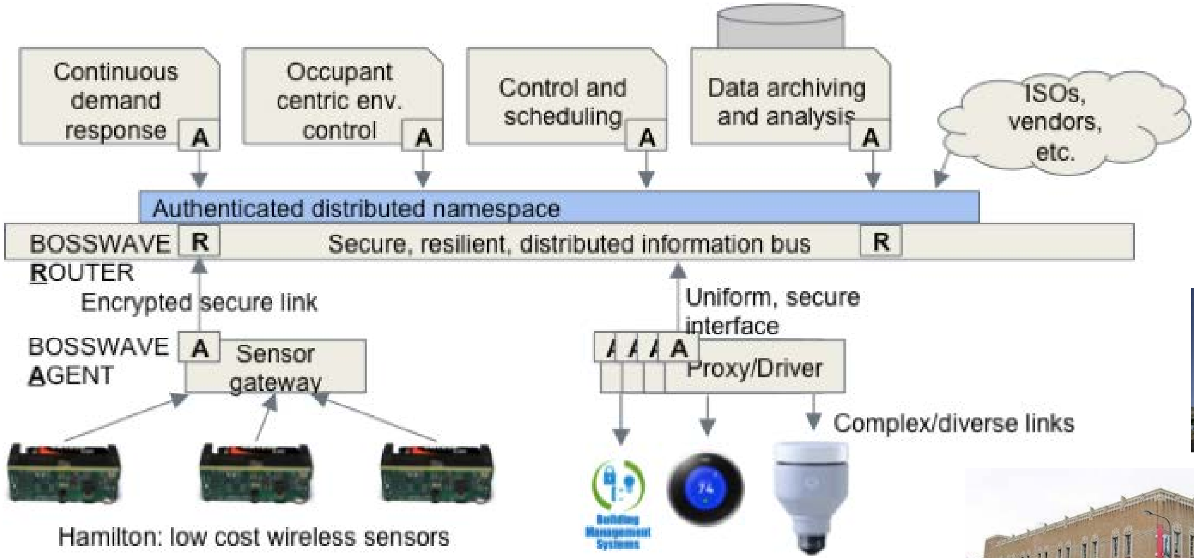
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Hamilton: Flexible, Open Source $10 Wireless Sensor System for Energy Efficient Building Operation



University of California, Berkeley

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Project Summary

Timeline:

Start date: October 1, 2016

Planned end date: September 30, 2019

Key Milestones

1. **Milestone 6.1** Second-generation sensor node with application-specific sensor modalities streaming samples at 1 hertz (Hz). (March 30, 2018)
2. **Milestone 8.1:** Demonstrate subsecond latency of application control component actuating a building device, such as a thermostat, (June 30, 2018)
3. **Milestone 9.2:** Applicability study of potential building product incorporation of project technology. (Sept 30, 2018)

Budget:

Total Project $ to Date (Dec 31, 2017):

- DOE: $496,690
- Cost Share: $86,273

Total Project $:

- DOE: $1,586,856
- Cost Share: $176,372

Key Partners:

UC Berkeley: Building, Energy, & Transportation Systems (BETS) in Computer Science California Institute for Energy & Environment (CIEE) Center for the Built Environment (CBE) Center for Information Technology Research in the Interest of Society (CITRIS)
Building Robotics and HamiltonIOT

Project Outcome: create and evaluate the technological foundations for secure and easy to deploy building energy efficiency applications utilizing pervasive, low-cost wireless sensors integrated with traditional Building Management Systems (BMS), consumer-sector building components, and powerful data analytics—and to demonstrate the effectiveness of this foundation on potential applications.

First objective, *Low Cost Wireless Sensor Systems*, develops networked sensors to provide situational awareness for optimization of environmental conditioning, lighting and other building functions at a total cost of manufacturing of less than $10 per sensor. The objective of the *Secure Attack-Resistant Middleware Tier* is to provide a resilient, secure, fully distributed information bus. The objective of the *Applications, Components and Services* tier is to integrate these technological advances into a complete building-wide secure system utilizing pervasive sensing and fine grain authorization to spur innovation in building energy efficiency.

Team

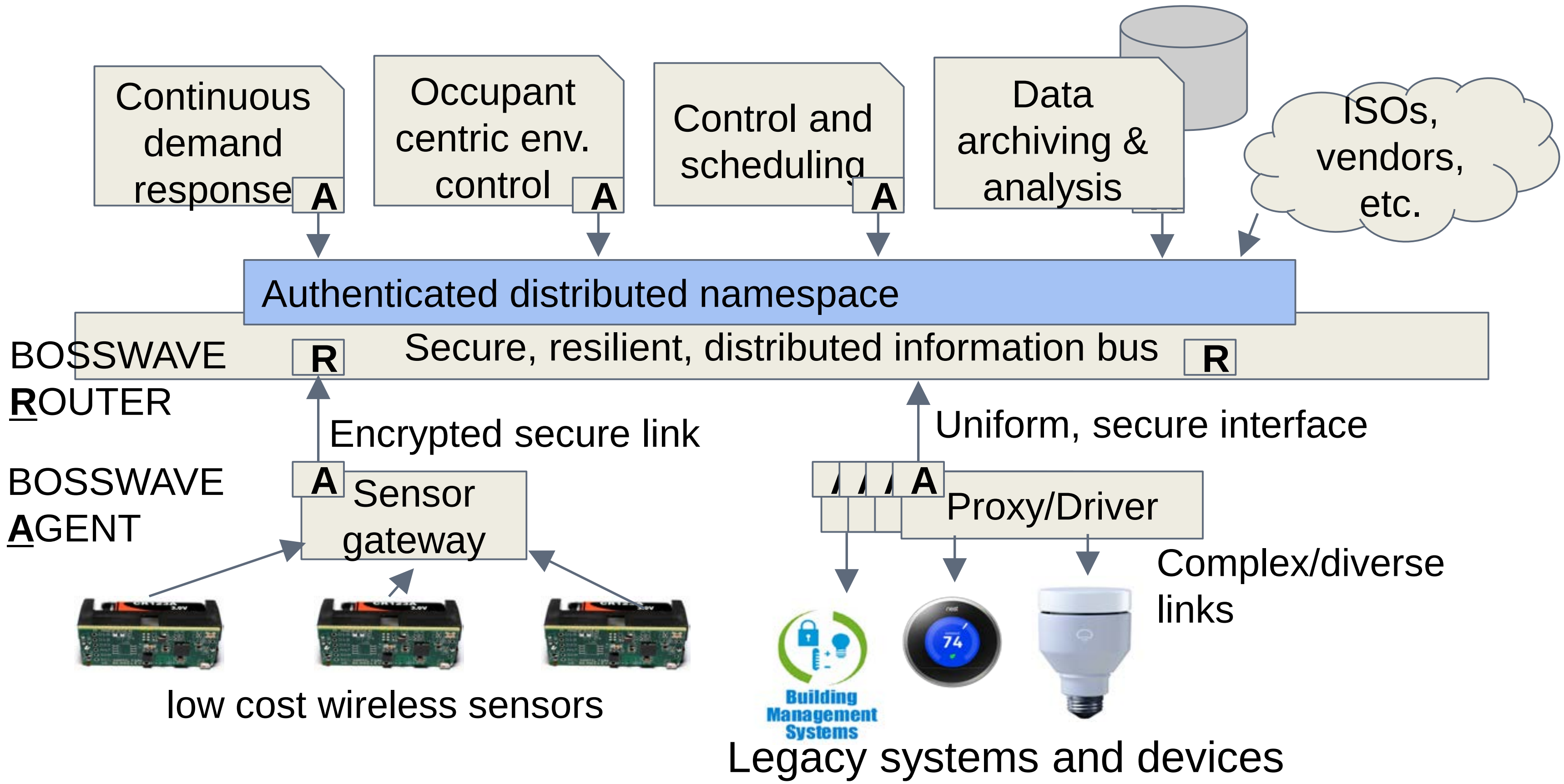
- BETS: hardware and software development, laboratory and pilot testing.
- CIEE: administration and T2M, Hamilton field deployments, thermostat hardware application.
- HamiltonIOT: device, data aggregation hosting and services
- BuildingRobotics (Comfy): consulting on integration of sensors into software application of HVAC comfort control and optimization
- CBE: Hamilton field deployment, anemometer and foot warmer hardware application.
- BRICK consortium: comprehensive, semantic-based metadata

Challenge: Bringing Wireless Sensor Systems into Building sector …

- Despite need – spend 70% of electricity & 90% of our lives, yet 2/3rds of occupants uncomfortable; could be natural counterbalance to fluctuating renewables…
- Buildings remain opaque, complex, inefficient, and often operating under degraded conditions, …
- Wireless sensor systems could provide visibility, but
  - devices remain too expensive, too hard to integrate into products
  - networks too hard to deploy at low power, high reliability
  - Programming too esoteric
- Need robust environment for applications, analytics & advanced control
  - With advanced security and cyber-protection
  - delegation of authority across administrative domains

Approach

- Create low cost building-wide extensible sensing fabric, secure attack-resistant communications infrastructure, and rich platform for advanced building services.

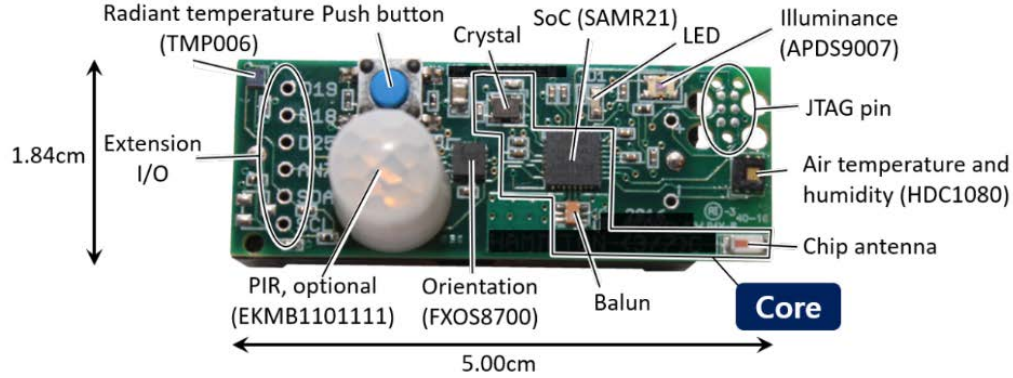


Impact

- **Design, implementation, and demonstration of novel sub-$10 WSS opens broad paths to market**
  - Open source HW& SW with deep design-for-manufacturing, design-time drop-in modularity, plus Open, thread-based TCP-IP,
  - Enables vendors to rapidly incorporate technology into product lines and develop applications and services
  - new market entrants, as well as pathways for established players
- **Secure, attack-resistant middleware provides protected, easy-to-use means of integrating devices, subsystems and services throughout increasingly-advanced buildings, & across ensembles, between grid / building / EV, etc., premises and cloud**
  - Mitigates most profound threat to technological advance in Building Technologies
- **Multi-building rich demonstrations (with Energy Commission) build key awareness of technological & market options**

Progress - Overview

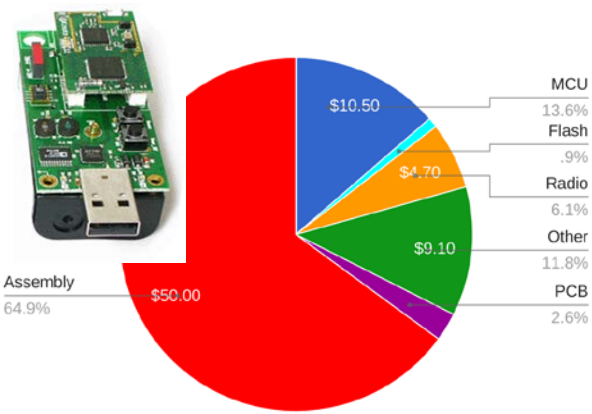
- **Work to date (18 months) is under budget and on time:**
  - **Two iterations** of a functional sensor system at a total manufacturing cost <$10; testing different types of sensors



  - Functional embedded operating system and low-power networking stack.
  - Functional distributed authorization/authentication system
  - Initial integration with BMSs, thermostats, electric meters, lighting
  - Over a dozen deployments with 10-40 sensors in each deployment
  - Identified fit with market segments.
  - Integrate cloud services for trust-limited data analytics into BOSSwave framework.

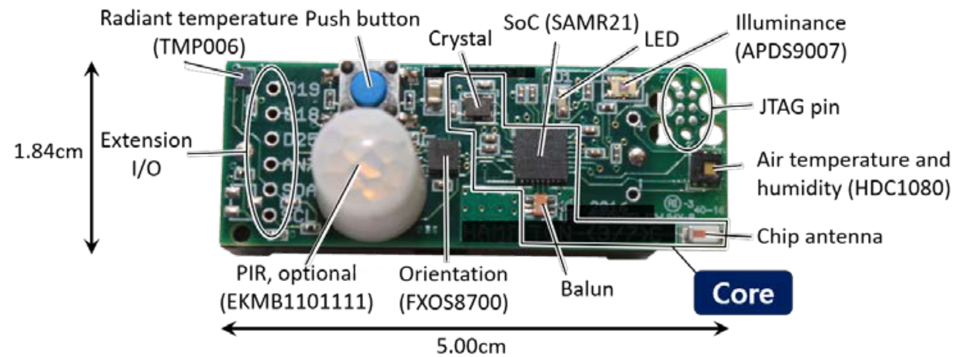
Transformative Wireless Sensor System

Traditional WSS



SOC module - Storm

Hamilton post-SOC WSS

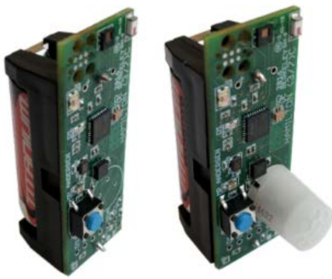


	Storm	Decimote
MCU	7.06 USD	4.58 USD
Flash	3.18 USD	
Radio	2.8 USD	
RF frontend	2.73 USD	0.91 USD
Oscillators	0.57 USD	0.66 USD
Assembly	12.00 USD	0.6 USD
Total	30.00 USD	6.75 USD

- Eliminate previously-dominant assembly costs
- Drop-in Open IP for application-specific design-for-mfg

Hamilton Open Ecosystem

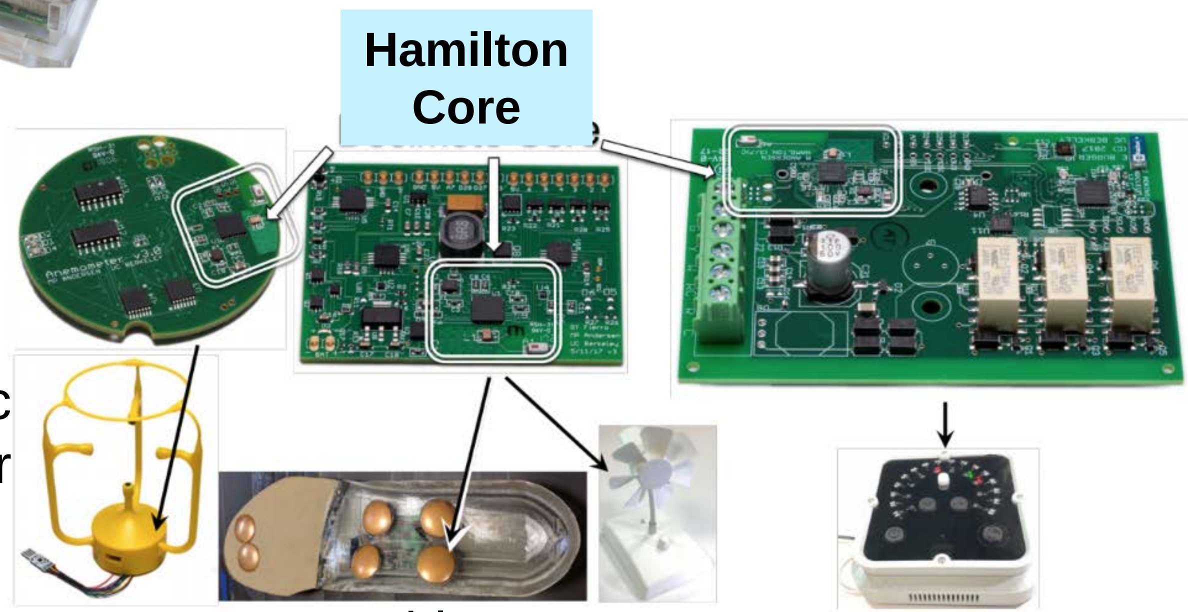
Building-Wide Environment Monitoring



Reliable Border Router

USB router

Personalized Environmental Control



Ultrasonic Anemometer

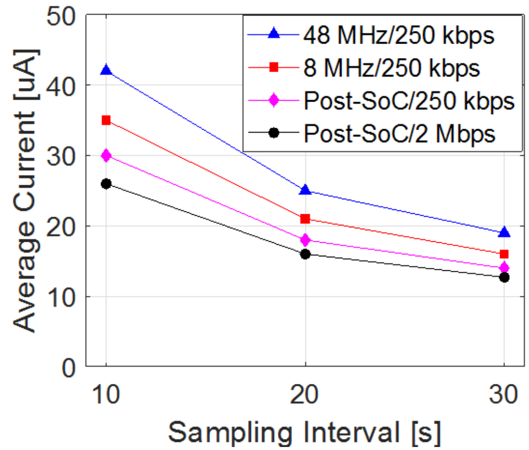
Smart Wearables

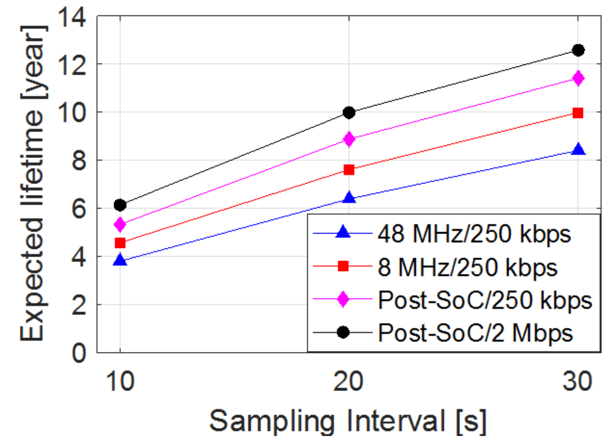
Smart Furniture

Post-SOC embedded Operating System

1st low idle power @ 32-bits

	Idle Current
TelosB/TinyOS	8.9 μA
Storm/TinyOS	13.0 μA
Firestorm/TinyOS	25.6 μA
TelosB/Contiki	36 μA
OpenMote/Contiki	2169 μA
CC2650STK/Contiki	13.2 μA
Decimote/Contiki	347 μA
TelosB/RIOT	1926 μA
SAMR21-XPRO/RIOT	6012 μA
Decimote/RIOT	5.9 μA (2.6 μA core)





Efficient Concurrency

	Preempt	Yield
TelosB/TinyOS (4 MHz)	38.9 μs	21.0 μs
TelosB/Contiki (4 MHz)	87.6 μs	72.0 μs
Decimote/Contiki (48 MHz)	5.84 μs	4.36 μs
TelosB/RIOT (4 MHz)	92.2 μs	83.0 μs
Decimote/RIOT (4 MHz)	79.4 μs	74.6 μs
Decimote/RIOT (48 MHz)	8.30 μs	7.76 μs

Efficient Sensing

	No DMA	DMA
ADC Sample Time	643 μs (busy)	599 μs (idle)
I2C Read Time	587 μs (busy)	492 μs (idle)

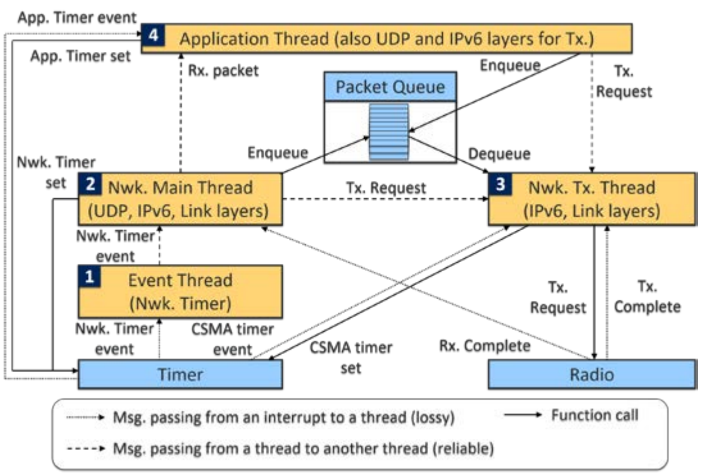
Decimote = Hamilton

- **Very low cost, idle power, scheduling overhead**
- **Embedded OS designs have been based on event-driven execution and specialized network stacks to achieve low-power and high concurrency**
- **Highly optimized Post-SOC design permits threads & TCP/IP stack for application innovation (redesign/implementation of RIoT)**
- **Advanced clock domain & rate management**

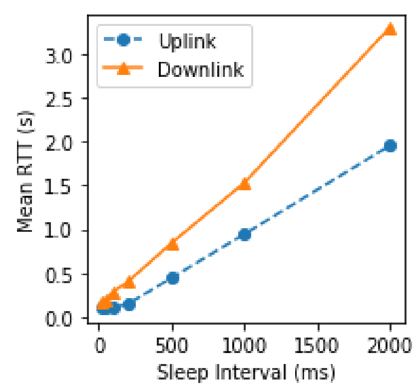
Advanced Network Stack

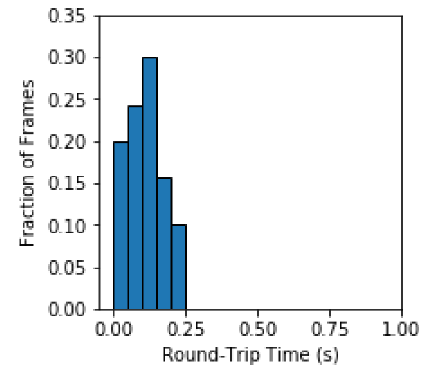
Study	[59]	[30]	[38]	[32][31]	[17]	This Paper (SAMR21 Platform)
TCP Stack	uIP	uIP	BLIP	Arch Rock	Linux	*TCPlp* (RIOT OS, OpenThread)
Max. Seg Size	1 Frame	4 Frames	1 Frame	1024 bytes	???	5 Frames
Window Size	1 Seg.	1 Seg.	1 Seg.	1 Seg.	variable	1848 bytes (4 Seg.)
Goodput (One Hop)	1.5 kb/s	12 kb/s	4.8 kb/s	15 kb/s	???	75 kb/s
Goodput (Multi-Hop)	0.55 kb/s[1]	12 kb/s	2.4 kb/s	9.6 kb/s	16 kb/s	20 kb/s

Table 1: Comparison of *TCPlp* to existing TCP implementations used in network studies over 802.15.4 networks



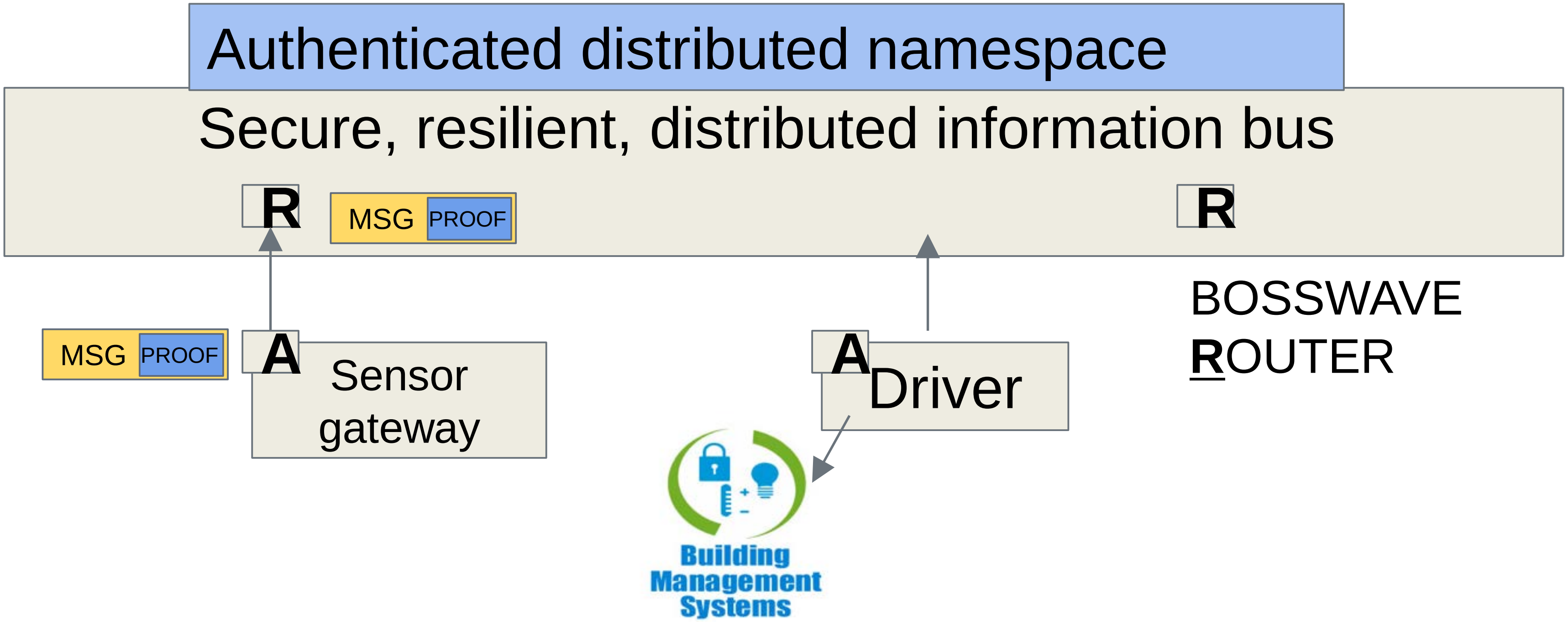
Platform	CPU Arch.	ROM (Code)	RAM (Data)
TelosB	16-bit, 25 MHz	48 kB	10 kB
SAMR21	32-bit, 48 MHz	256 kB	32 kB
Firestorm	32-bit, 48 MHz	512 kB	64 kB
Rasp. Pi	32-bit, 700 MHz	SD Card	256 MB





- **Redesign/Implementation of OpenThread and FreeBSD TCP/IP stack for low-power, reliable communication**

WAVE concept

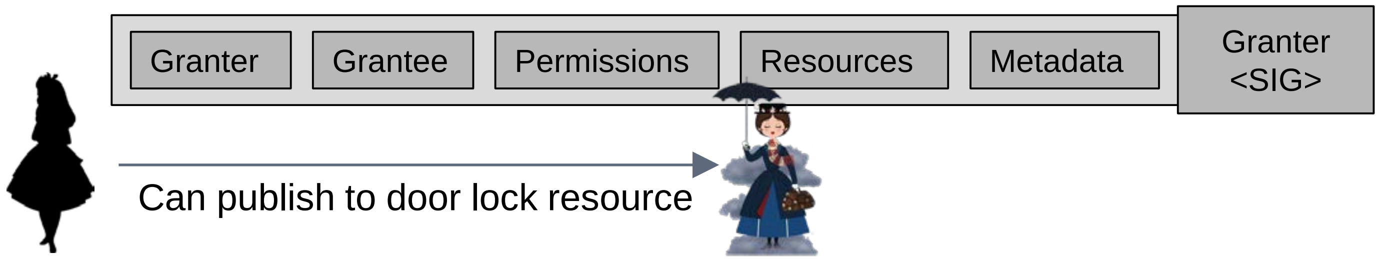


Multiple generations of BOSSwave router/agent

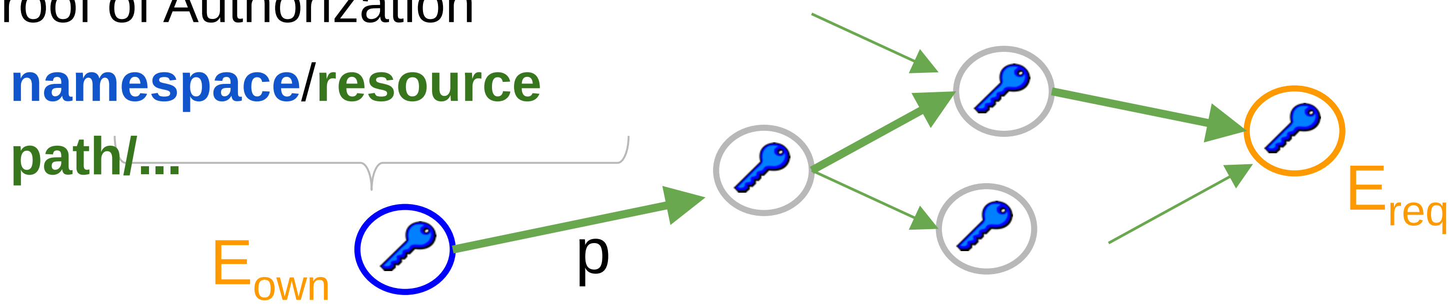
- Tracked, contributed to, & evaluated Ethereum Block Chain micro-contract technology
- Secure encapsulation of commercial technology and direct realization
- Fine-grained dynamic delegation of trust, continuously verified

Bldg-City-Grid Scale Attack-Resistant Comm.

Delegation of Trust



Proof of Authorization



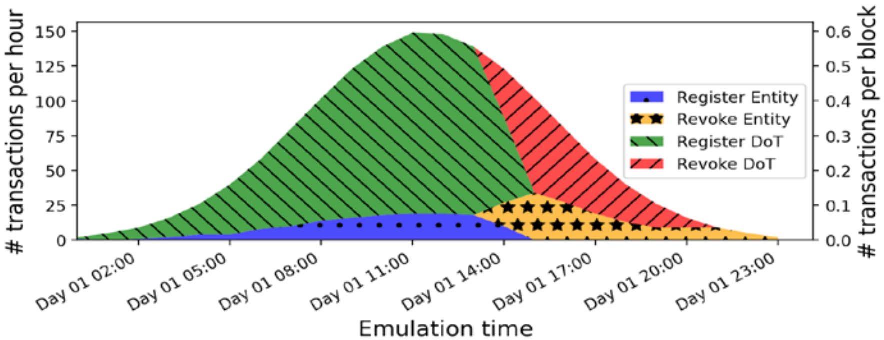
- Designed to support delegation of permission across administrative domains, which is fundamental to building operations
- Authentication & Authorization built-in to fundamental communication primitives
- Requestor must present *proof of authorization* with every request
  - Validated by communication fabric and Receiver
- Fully distributed, without relying on any central authority or vendor

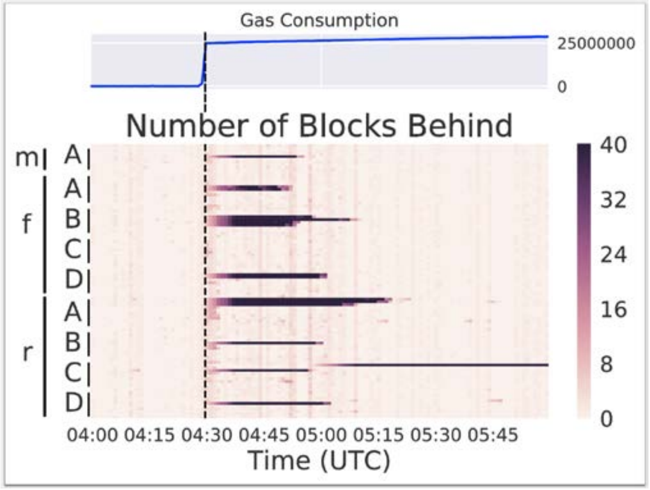
Demonstrations of WAVE Scale and Resilience

Type	Entities	DoTs granted	Avg Out°
Occupant	951,293	1,312,005	1.38
Apt Owner	15,787	529,562	33.54
Apt Bldg	40,921	40,921	1
Apt Lease	264,781	264,781	1
House Title	95,931	95,931	1
Thermostat	360,712	N/A	N/A
Meter	360,712	N/A	N/A
Utility	603	722,026	1197.39
Total	2,090,740	2,965,226	1.42

Processing

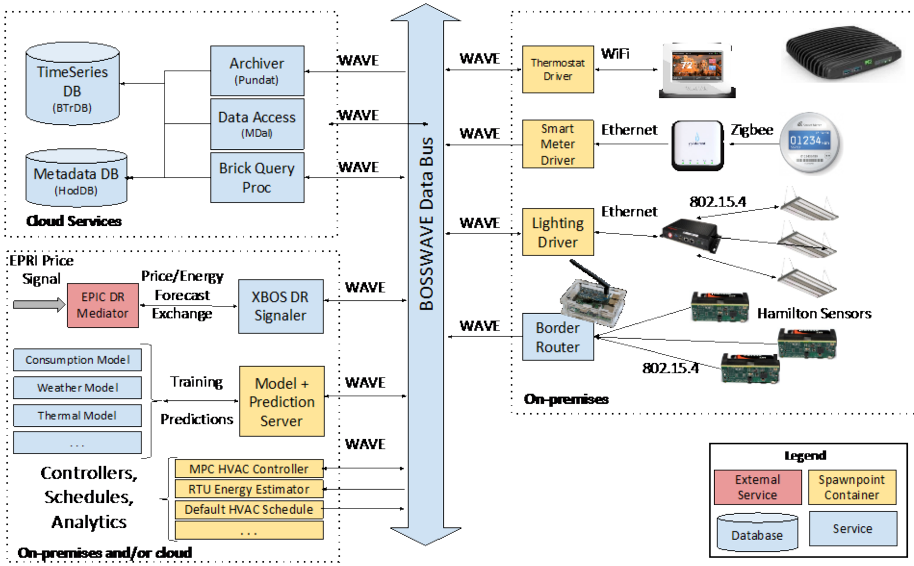
Type	Idle (1h)	Normal (30h)	Attack (4h)
M,10,20,x64	3.80±0.72	3.96±0.26	4.84±0.75
A,45,20,x64	0.04±0.01	0.03±0.01	0.59±0.30
A,45,2,x64	0.05±0.01	0.03±0.01	0.48±0.32
A,1,20,armv7	0.46±0.08		1.39±0.10
A,2,2,armv7	0.15±0.01		1.58±0.11
A,1,20,atom	1.22±0.14		1.37±0.09
A,1,2,atom	0.47±0.06		0.61±0.10





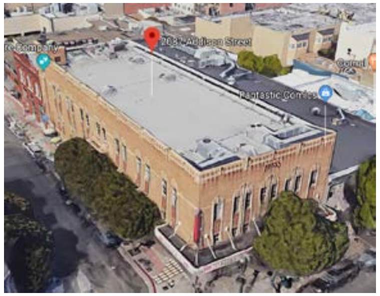
- Emulated churn of Energy Services DoTs at full San Francisco scale (thermostatic load mgmt.)
- Evaluated massive attack scenarios

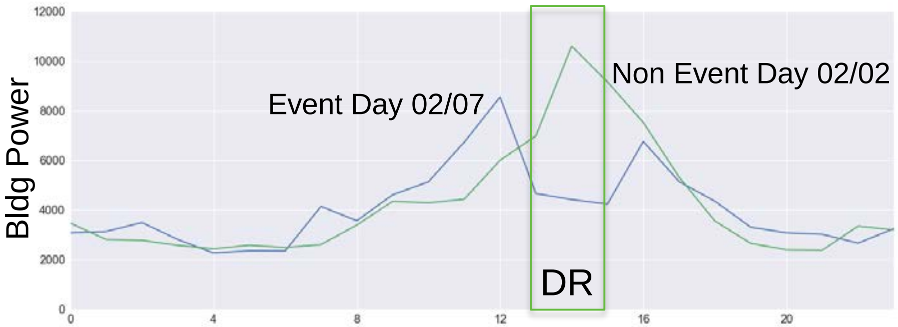
Rich Scalable Bldg Services Infrastructure



CIEE: 7.5k sq ft, 1 floor

5 RTU





- Rapid assembly of portable building application
- Driven from semantically rich metadata
- Modern container from cloud to on-premises

Stakeholder Engagement

We are halfway through the project

- **Very strong engagement internally and externally**
  - UCB CS team developing technology closely with CIEE team connected to Field Studies & Market
- Five papers published and presented at conferences
- The technology has been presented at multiple university-industry meetings
- Interest from
  - Building component manufacturers (Sage Glass. Armstrong, Price)
  - Building service software (Comfy, BuildingOS, Harmony.ai)
  - Architecture and engineering firms (Perkins and Will/Architecture, Integral Group/ Green Engineering, LPA inc./Sustainable Design Architecture Firm, Ingersoll Rand, Genentec/campus buildings, Intel)
  - Academic and start-up research (CBE/UC Berkeley, Prof. Ko/Korea University Hospital, Alsen, ChirpMicro)
  - Data management--BTrDB (PingThings)
  - Standards organizations (ASHRAE—BRICK)

Remaining Project Work

In the next 18 months:

- Identify component offerings that advance the sensor system design through detailed design study of new offerings from the relevant industry providers.
- More advanced and more fully integrated analytics and control algorithms, e.g., Learning-based models, schedules, etc.
- Continue to deploy and evaluate building scale proof point.
- Assess the secure, attack-resistant middleware theoretically and empirically.

- Demonstrate functionality with building applications providing occupant-centered control and continuous demand response.
- Identify how the technology developed could be utilized for securing and authenticating the delivery of a demand responsive event.
- Assess the potential market inclusion of the developed technology and application solutions.

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: The project is within budget.
Variances: No variances or changes to project plan (**the current expenditures are slightly under budget, but expected to catch up).**
Cost to Date: We have spent about 40% of the DOE share and 60% of the cost share.
Additional Funding: Deployments and hardware applications have leveraged other projects funded by California Energy Commission and ARPA-E.

Budget History					
October 1, 2016 – FY 2017 (past)		FY 2018 (current)		FY 2019 – September 30, 2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$387,360	$74,074	$429,003	$55,848	$770,494	$46,450

Project Plan and Schedule

Project Start: October 1, 2016
Projected End: September 30, 2019