The Tactile Internet: Where Do We Go From Here?

Martin Maier

University of South Florida, Tampa, April 17, 2019

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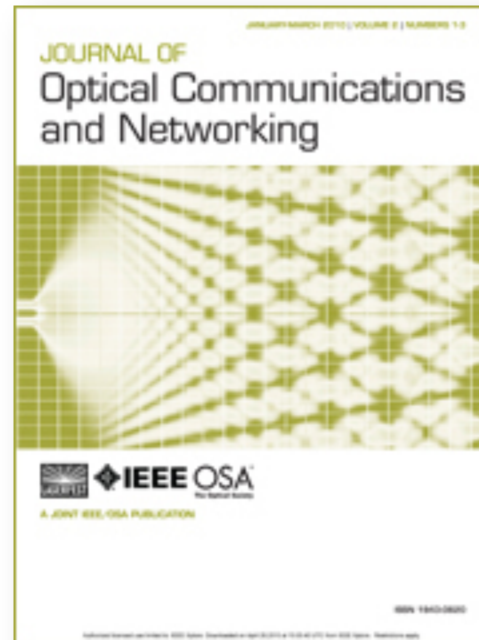
IEEE/OSA JOCN Special Issue on Latency in Edge Optical Networks

April 2019:

M. Maier and A. Ebrahimzadeh

"Towards Immersive Tactile Internet Experiences: Low-Latency FiWi Enhanced Mobile Networks With Edge Intelligence [Invited]"



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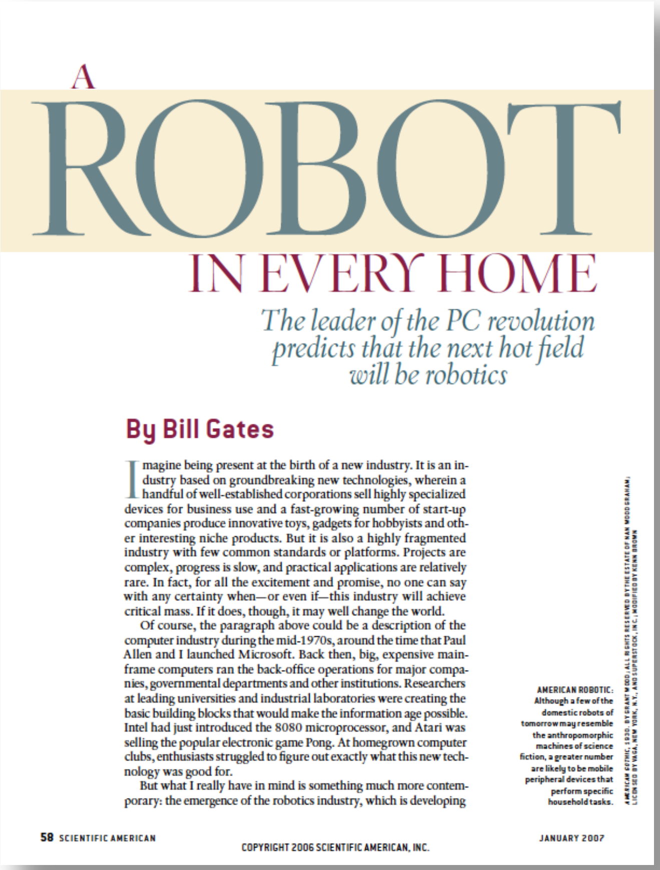
“A Robot in Every Home”

Bill Gates, 2007:

- Robotics industry is developing in much the same way as PC business did 30 years ago

- Vision: PC will get up off the desktop & allow us to see, hear, touch and manipulate objects remotely



A ROBOT IN EVERY HOME

The leader of the PC revolution predicts that the next hot field will be robotics

By Bill Gates

Imagine being present at the birth of a new industry. It is an industry based on groundbreaking new technologies, wherein a handful of well-established corporations sell highly specialized devices for business use and a fast-growing number of start-up companies produce innovative toys, gadgets for hobbyists and other interesting niche products. But it is also a highly fragmented industry with few common standards or platforms. Projects are complex, progress is slow, and practical applications are relatively rare. In fact, for all the excitement and promise, no one can say with any certainty when—or even if—this industry will achieve critical mass. If it does, though, it may well change the world.

Of course, the paragraph above could be a description of the computer industry during the mid-1970s, around the time that Paul Allen and I launched Microsoft. Back then, big, expensive mainframe computers ran the back-office operations for major companies, governmental departments and other institutions. Researchers at leading universities and industrial laboratories were creating the basic building blocks that would make the information age possible. Intel had just introduced the 8080 microprocessor, and Atari was selling the popular electronic game Pong. At homegrown computer clubs, enthusiasts struggled to figure out exactly what this new technology was good for.

But what I really have in mind is something much more contemporary: the emergence of the robotics industry, which is developing

AMERICAN ROBOTIC: Although a few of the domestic robots of tomorrow may resemble the anthropomorphic machines of science fiction, a greater number are likely to be mobile peripheral devices that perform specific household tasks.

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“The Tactile Internet”

March 2014:

- G. P. Fettweis coins the term Tactile Internet:
    - *“Enabling unprecedented mobile applications for tactile steering and control of real and virtual objects”*

August 2014:

- ITU-T Technology Watch Report “The Tactile Internet”

"The Tactile Internet"

IEEE Advancing Technology for Humanity

March 2016:

- IEEE P1918.1 standards working group approved by IEEE Standards Association
- Definition of Tactile Internet:
  - *"A network, or a network of networks, for remotely accessing, perceiving, manipulating or controlling real and virtual objects or processes in perceived real-time."*
- Key use cases
  - Teleoperation, haptic communications, and immersive virtual reality

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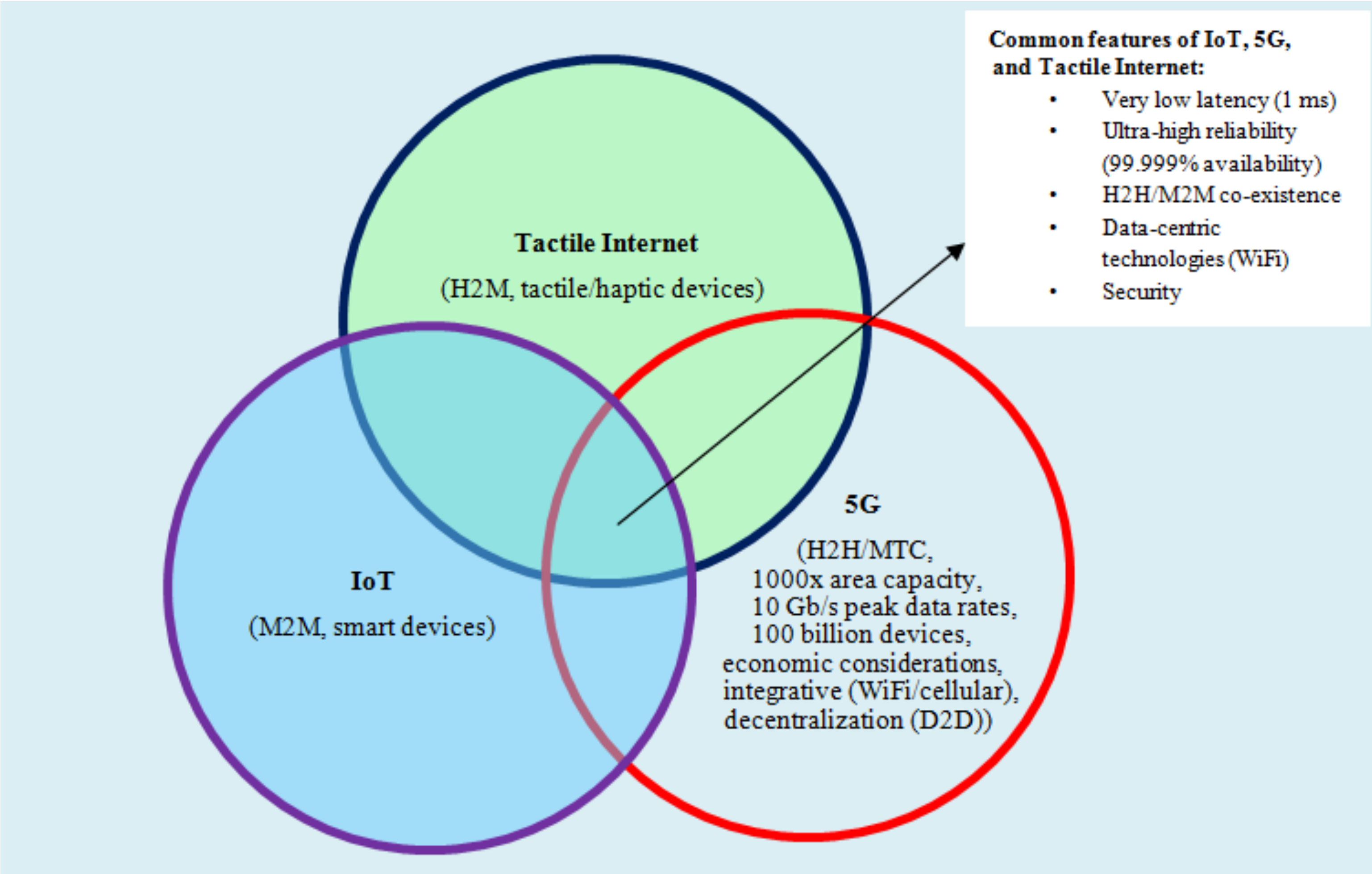
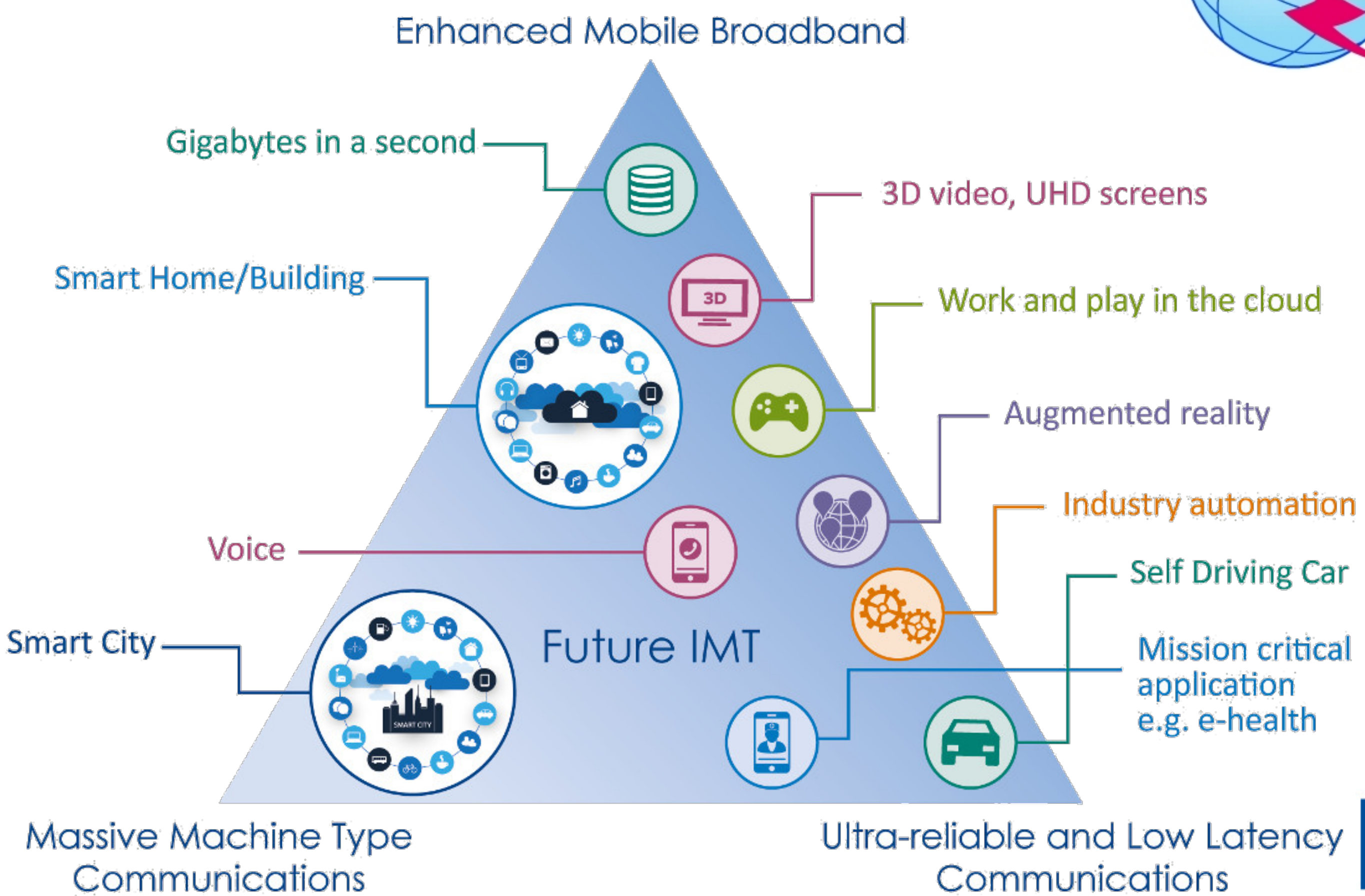
Tactile Internet vs. IoT & 5G



URLLC

International Telecommunication Union



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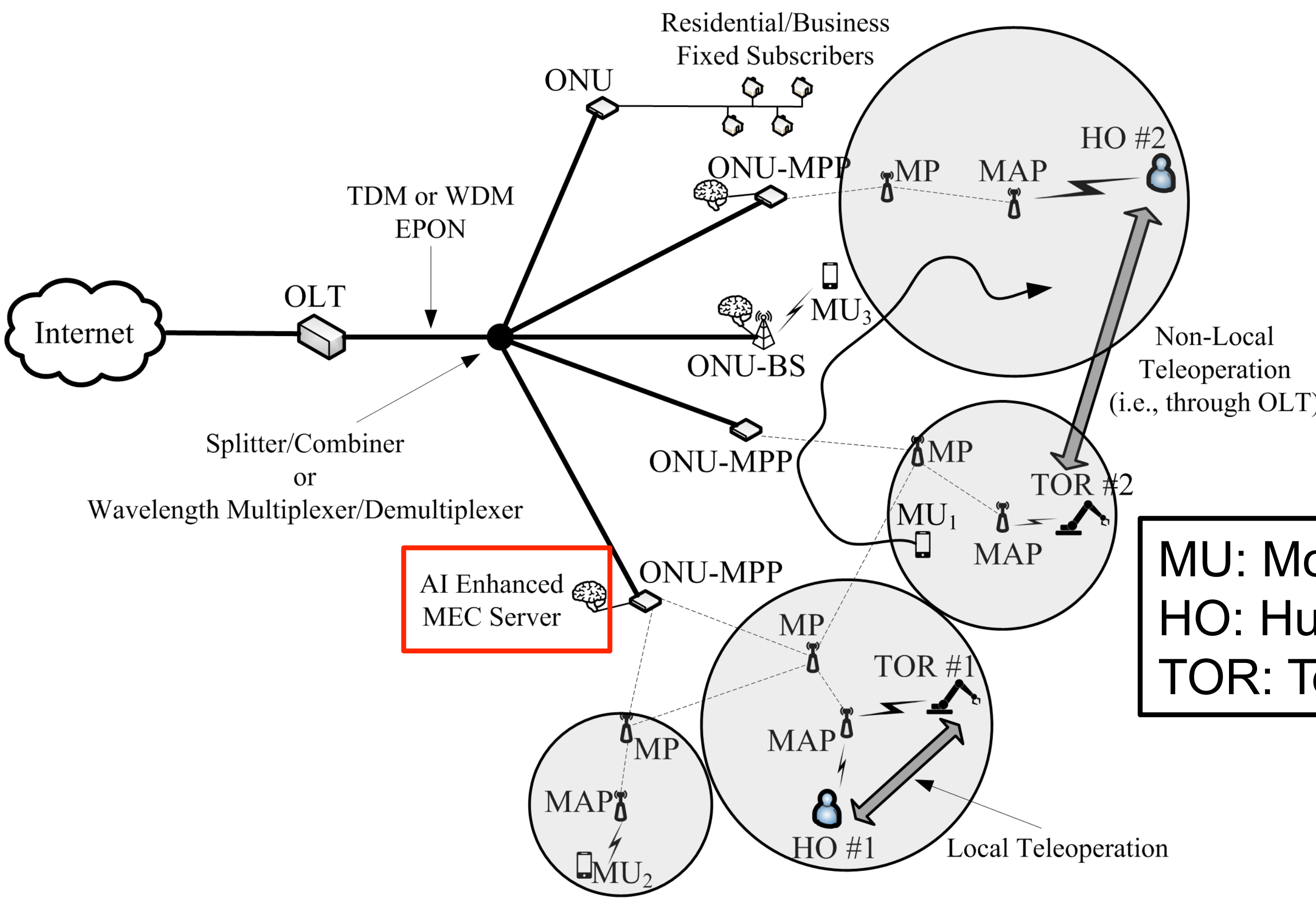
FiWi Enhanced 4G LTE-A HetNets



MU: Mobile User
HO: Human Operator
TOR: Teleoperator Robot

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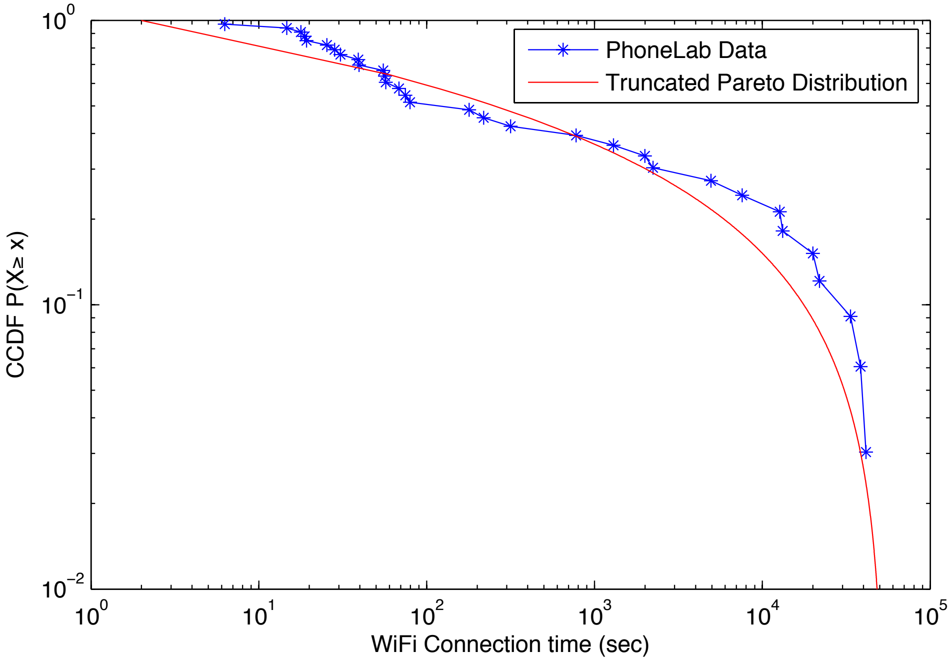
WiFi Connection Time of MUs

- CCDF of WiFi connection time of MUs fits truncated Pareto distribution:

$$\frac{\alpha\gamma^{\alpha}}{1-\left(\frac{\gamma}{\nu}\right)^{\alpha}} \cdot x^{-(\alpha+1)}, 0 < \gamma \leq x \leq \nu$$

- Verified by using comprehensive smartphone traces of PhoneLab data set



H. Beyranvand, M. Lévesque, M. Maier *et al.*, "Toward 5G: FiWi Enhanced LTE-A HetNets With Reliable Low-Latency Fiber Backhaul Sharing and WiFi Offloading," *IEEE/ACM Transactions on Networking*, vol. 25, no. 2, pp. 690-707, April 2017

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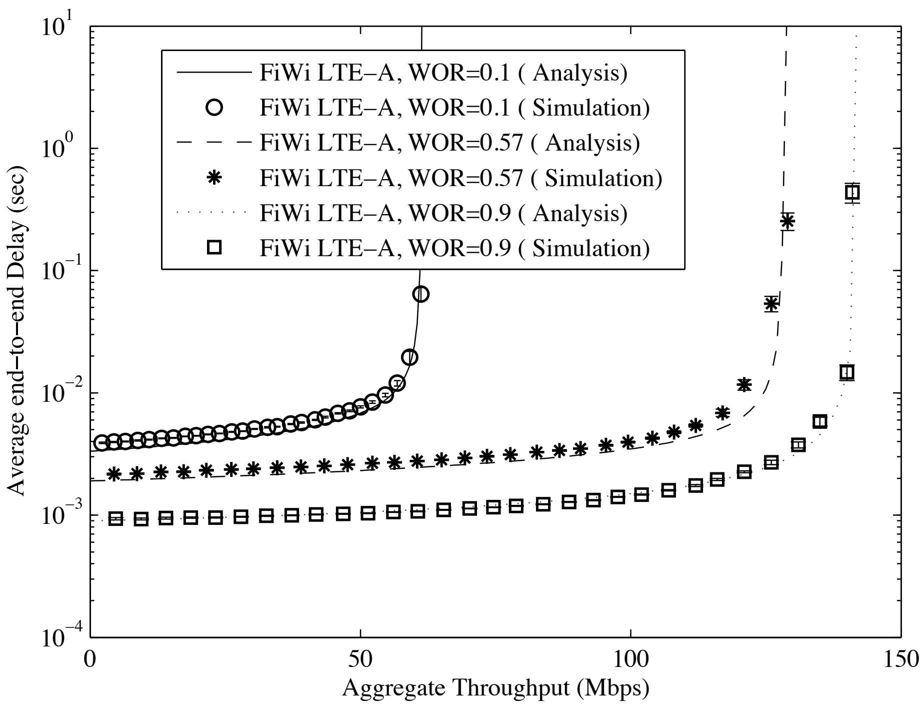
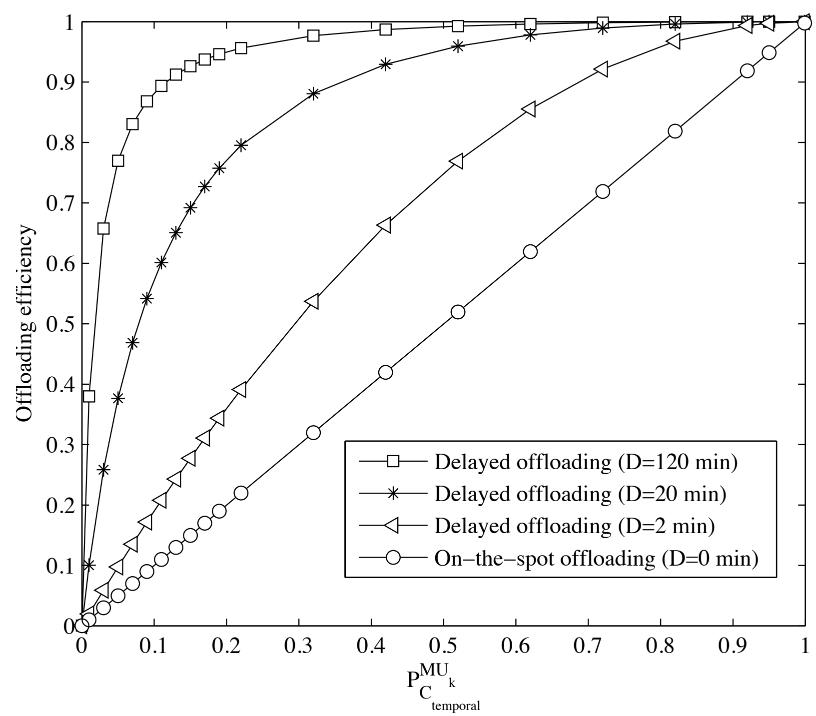
URLLC in FiWi Enhanced 4G LTE-A HetNets





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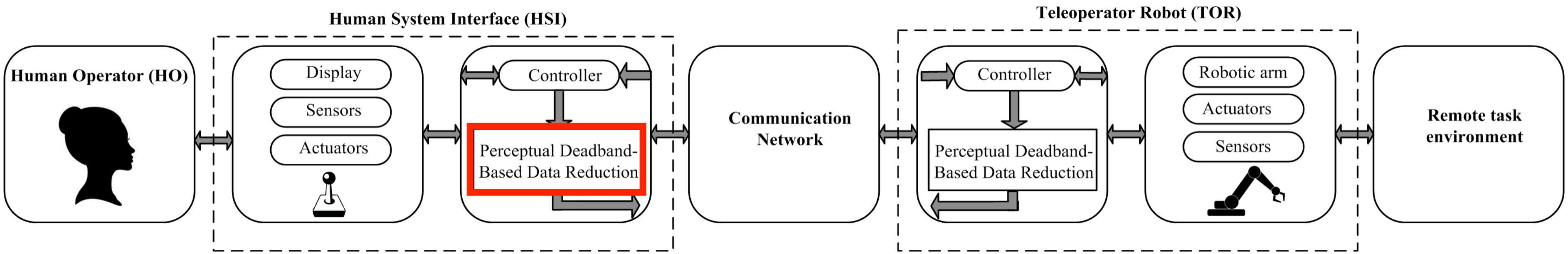
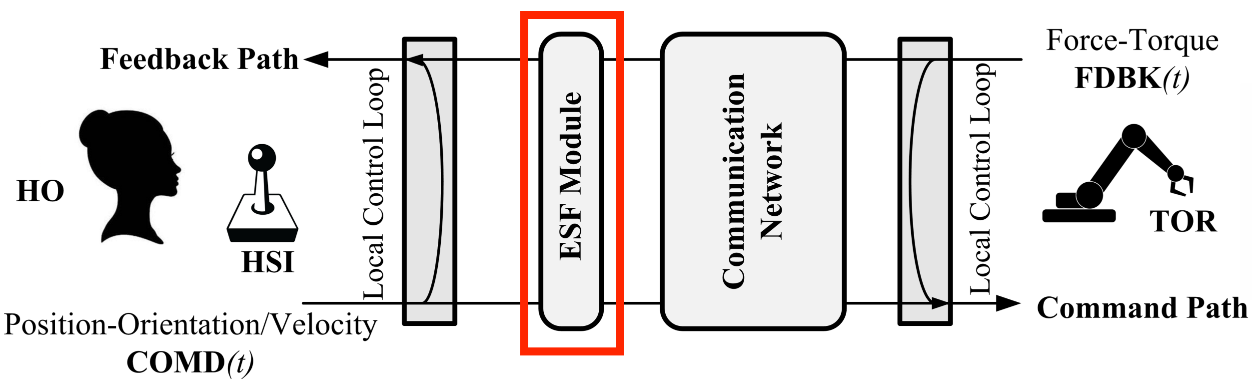
Teleoperation & Haptic Communications





Edge Sample Forecast (ESF) via AI Enhanced MEC

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ESF: Multi-Layer Perceptron (MLP)

Algorithm 1 Edge Sample Forecast

Input: $\mathcal{T}, \mathcal{S}, t_0, \Xi$
Output: θ^*

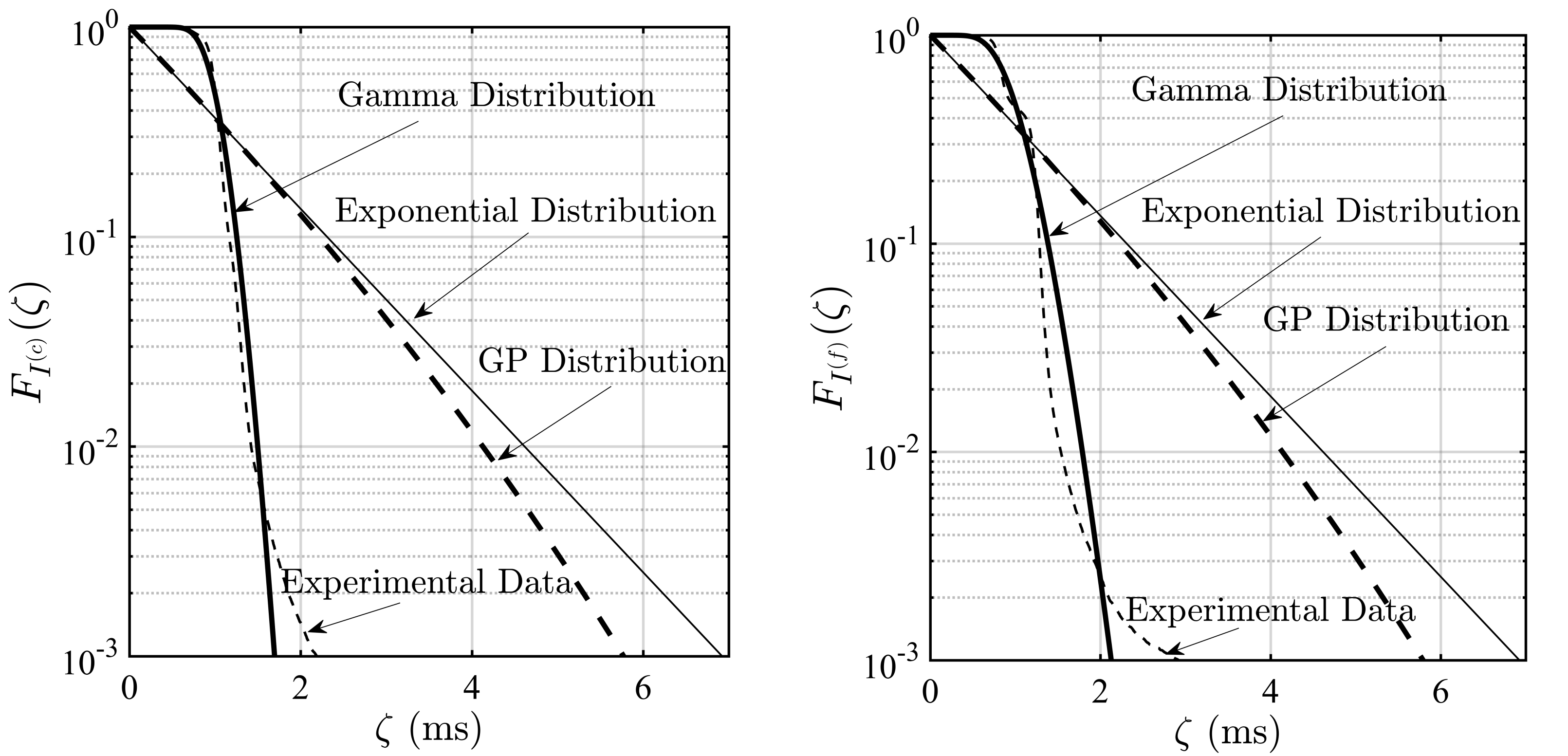
$\delta = 1/F_s$
$\mathcal{T}^\delta, \mathcal{S}^\delta =$ SAMPLE_ALIGNER$(\mathcal{T}, \mathcal{S}, \delta)$
$\Delta \leftarrow \left\lceil \frac{t_0 - \mathcal{T}^\delta(L)}{\delta} \right\rceil$
$\mathcal{A}_0 \leftarrow \left(s_1^\delta, \ldots, s_L^\delta\right) \in \mathbb{R}^L$
for $i = 1$ to Δ **do**
    $t_i^* \leftarrow t_L^\delta + i \times \delta$
    $\theta_i = \Psi\left(\mathcal{A}_{i-1}, \Xi\right)$
    $\mathcal{A}_i = (\mathcal{A}_{i-1}(2), \mathcal{A}_{i-1}(3), \ldots, \mathcal{A}_{i-1}(L), \theta_i)$
end for
$\theta^* \leftarrow \frac{\theta_\Delta - \theta_{\Delta-1}}{t_\Delta^* - t_{\Delta-1}^*}\left(t_0 - t_{\Delta-1}^*\right) + \theta_{\Delta-1}$
return θ^*

Algorithm 2 SAMPLE_ALIGNER()

Input: $\mathcal{T}, \mathcal{S}, \delta$
Output: $\mathcal{T}^\delta, \mathcal{S}^\delta$

$L \leftarrow \left\lceil \frac{t_K - t_1}{\delta} \right\rceil$
for $i = 1$ to L **do**
    $t_i^\delta \leftarrow t_1 + (i-1)\delta$
end for
$s_1^\delta \leftarrow s_1$
for $i = 2$ to L **do**
    $s_i^\delta \leftarrow \frac{s_j - s_{j-1}}{t_j - t_{j-1}}\left(t_i^\delta - t_{j-1}\right) + s_{j-1}, \forall j : t_{j-1} < t_i^\delta < t_j$
end for
return $\mathcal{T}^\delta, \mathcal{S}^\delta$

Haptic Traffic: Packet Interarrival Times



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Haptic Traffic: Packet Interarrival Times

	Without Deadband Coding	With Deadband Coding
Command path	**Gamma**	**Gamma** ($\forall d_c < 0.05\%$) **GP** ($\forall d_c \geq 0.05\%$)
Feedback path	**Gamma**	**Gamma** ($\forall d_f < 15\%$) **Poisson** ($\forall d_f \geq 15\%$)

(a)

	Without Deadband Coding	With Deadband Coding
Command path	**Deterministic**	**GP**
Feedback path	**Deterministic**	**GP**

(b)

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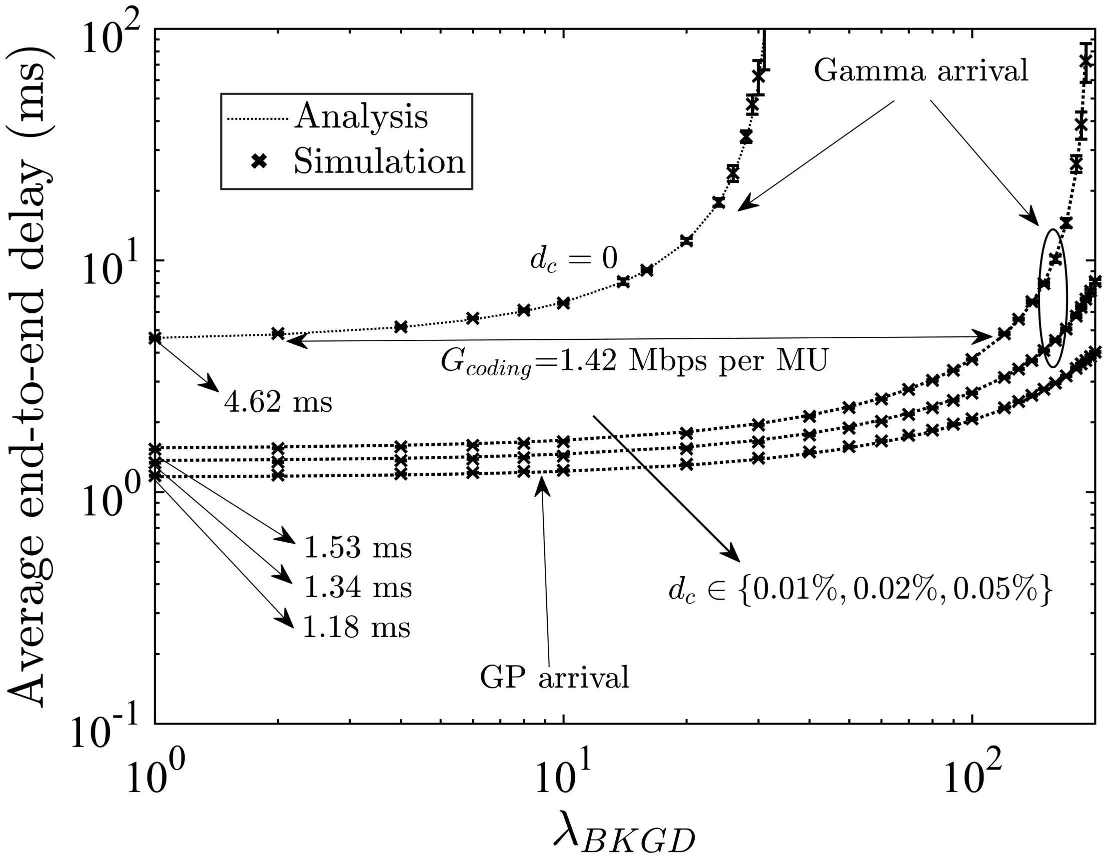
Haptic Trace Driven Simulations



Local teleoperation w/ and w/o deadband coding

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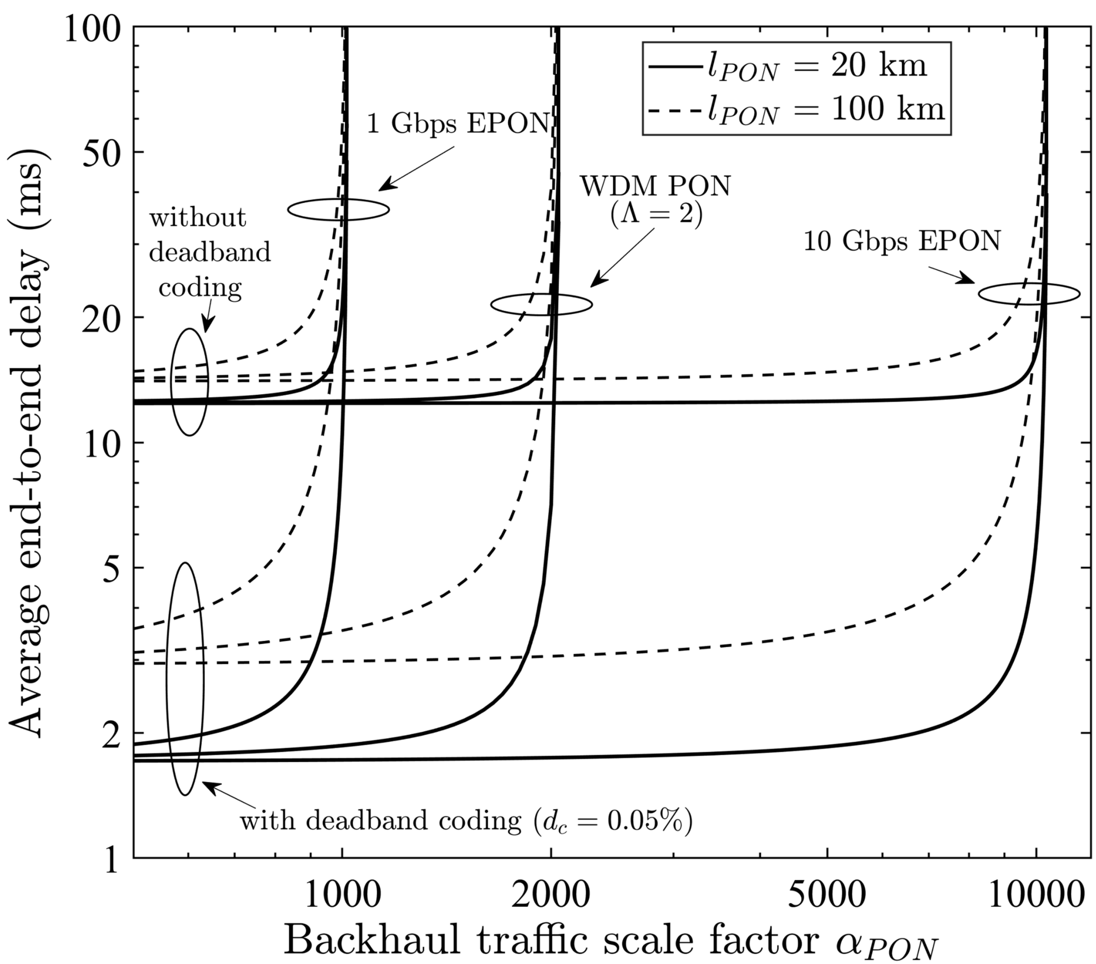
NG-PON Backhaul



Non-local teleoperation across different NG-PON backhaul infra-structures

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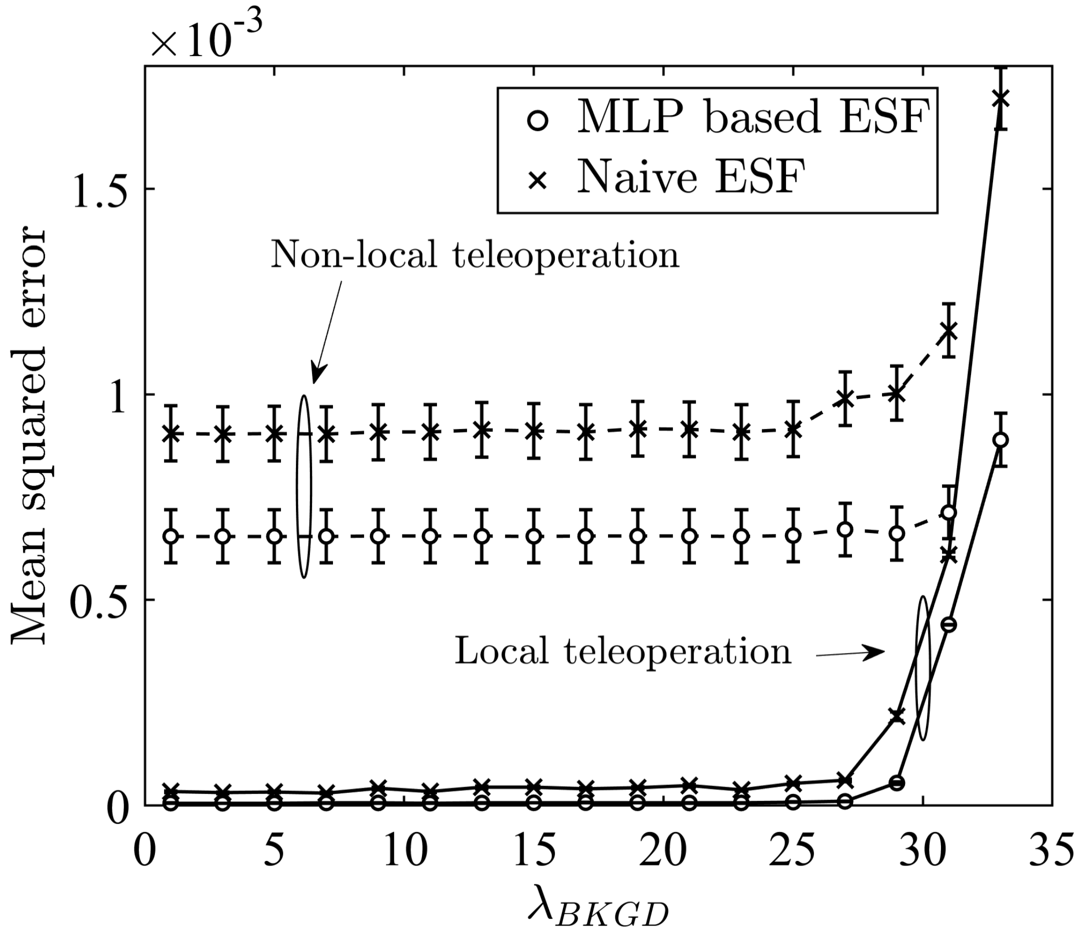
ESF: Forecasting Accuracy



Haptic traces used to train MLP based ESF to perceive remote task environment in real-time at 1-ms granularity

Intelligent Machines: Classification

Task Type	Human Support	Repetitive Task Automation	Context Awareness and Learning	Self-Aware Intelligence
Analyze numbers	Business intelligence, data visualization, hypothesis-driven analytics	Operational analytics, scoring, model management	Machine learning, neural nets	Not yet
Digest words, images	Character and speech recognition	Image recognition, machine vision	Watson, natural language processing	Not yet
Perform digital tasks (admin and decisions)	Business process management	Rules engines, robotic process automation	Not yet	Not yet
Perform physical tasks	Remote operation	Industrial robotics, collaborative robotics	Fully autonomous robots, vehicles	Not yet

Ability to act (vertical)

vs.

Ability to learn (horizontal)

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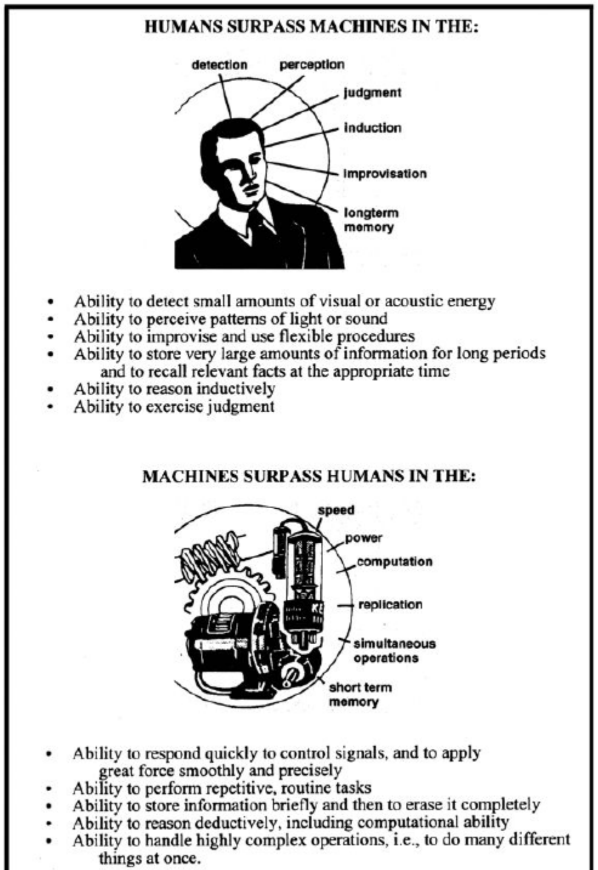
T. H. Davenport and J. Kirby, “Only Humans Need Apply: Winners and Losers in the Age of Smart Machines,” HarperBusiness, May 2016.

HABA/MABA


HUMANS SURPASS MACHINES IN THE:

- Ability to detect small amounts of visual or acoustic energy
- Ability to perceive patterns of light or sound
- Ability to improvise and use flexible procedures
- Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time
- Ability to reason inductively
- Ability to exercise judgment

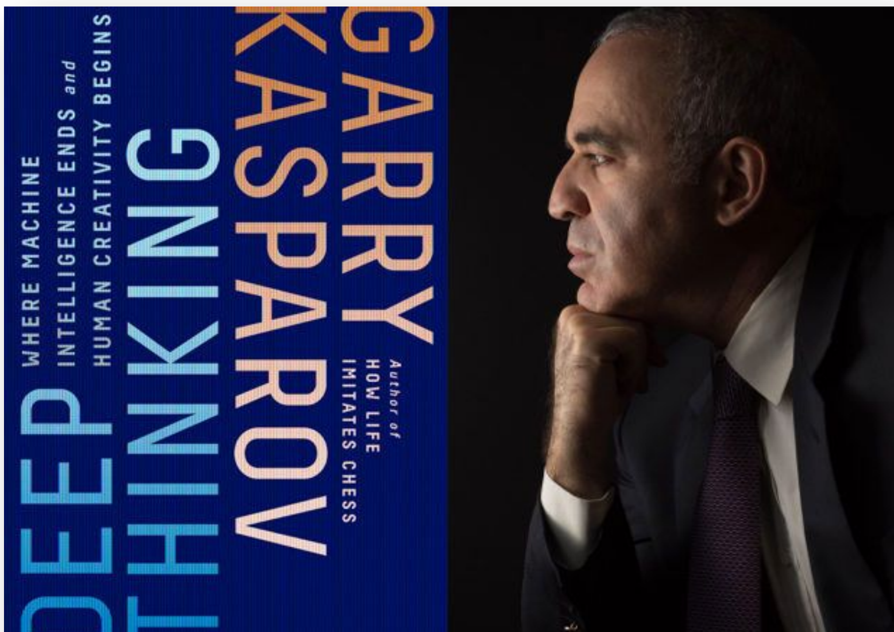
MACHINES SURPASS HUMANS IN THE:

- Ability to respond quickly to control signals, and to apply great force smoothly and precisely
- Ability to perform repetitive, routine tasks
- Ability to store information briefly and then to erase it completely
- Ability to reason deductively, including computational ability
- Ability to handle highly complex operations, i.e., to do many different things at once.

"Human Engineering for an Effective Air Navigation and Traffic Control System," *National Academy of Sciences*, 1951.

- Traditional humans-are-better-at/ machines-are-better-at (HABA/MABA) design approach
- Only divides up work between humans and machines

Human-Machine Collaboration



Weak human + Machine + Better process

superior to

Strong human + Machine + Inferior process

A <u>clever process</u> beats superior knowledge & superior technology

From AI to IA (Intelligence Amplification)

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Human-Agent-Robot Teamwork (HART)

Basic Idea: “Keep Human in the Loop”

- Treating human as a “member” of a team of intelligent machines for a race with (rather than against) machines

Goals:

- Design of human-machine coordination processes
- Drive symbiotic human-robot development in search for synergies
- Enabling automation and/or augmentation of physical and cognitive human tasks

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Physical Task Allocation Using Self-Awareness

Given:

- J_i: Task i, $(i = 1, 2, \ldots)$.
- t_i^a: Arrival time of task demand i.
- w_i: Workload brought in by task i.
- l_i^{task}: Location of task i.
- S_{UO}^A: Set of available user-owned robots.
- S_{UO}^B: Set of busy user-owned robots.
- S_{NO}^A: Set of available network-owned robots.
- S_{NO}^B: Set of busy network-owned robots.
- S: Set of all user- and network-owned robots.
- N: Total number of robots.
- l_j^r: Location of robot j.
- t_j^{av}: Next available time of robot j.
- v_j: Speed of robot j.
- C_j: Task processing capacity of robot j.
- D: Maximum scheduling deadline.
- $d(l_j^r, l_i^{task})$: Euclidean distance between task i and robot j.

Decision variables:

- X_i^j: A binary variable equal to 1 if task i is assigned to robot j.

Objective:

$$\min \sum_{j=1}^{N} X_i^j \left(\overbrace{\max\left(t_j^{av} - t_i^a, 0\right)}^{\text{scheduling delay}} + \overbrace{\frac{d(l_j^r, l_i^{task})}{v_j}}^{\text{traversing time}} + \overbrace{\frac{C_j}{w_i}}^{\text{execution time}} \right),$$

subject to

$$\sum_{j \in S_{UO}^A \cup S_{UO}^B} \left(t_j^{av} - t_i^a\right) X_i^j < D,$$

$$\sum_{j=1}^{N} X_i^j = 1,$$

$$X_i^j \in \{0, 1\}.$$

Algorithm 1 Self-Aware Multi-Robot Task Coordination

Input: $J_i, w_i, t_i^a, S_{UO}^A, S_{UO}^B, S_{NO}^A, S_{NO}^B, S, l_j^r, t_j^{av}, C_j, v_j, D$
Output: $X_i^j, t_j^{av}, l_j^r, \forall j = 1, 2, \ldots, N$

```
if S^A_UO ≠ ∅ then
  j* ← argmin_{j∈S^A_UO} d(l^r_j, l^task_i)
else
  if S^B_UO ≠ ∅ then
    W_min ← min_{j∈S^B_UO} (t^av_j − t^a_i)
    if W_min < D then
      j* ← argmin_{j∈S^B_UO} (t^av_j − t^a_i)
    else
      if S^A_NO ≠ ∅ then
        j* ← argmin_{j∈S^A_NO} d(l^r_j, l^task_i)
      else
        j* ← argmin_{j∈S} (t^av_j − t^a_i)
      end if
    end if
  end if
end if
X^{j*}_i ← 1
t^av_{j*} ← t^av_{j*} + max(t^av_{j*} − t^a_i, 0) + d(l^r_{j*}, l^task_i)/v_{j*} + C_{j*}/w_i
return X^j_i, t^av_j, l^r_j, ∀j = 1, 2, ..., N
```

HART-centric task coordination based on **shared use of user- and networked-owned robots**

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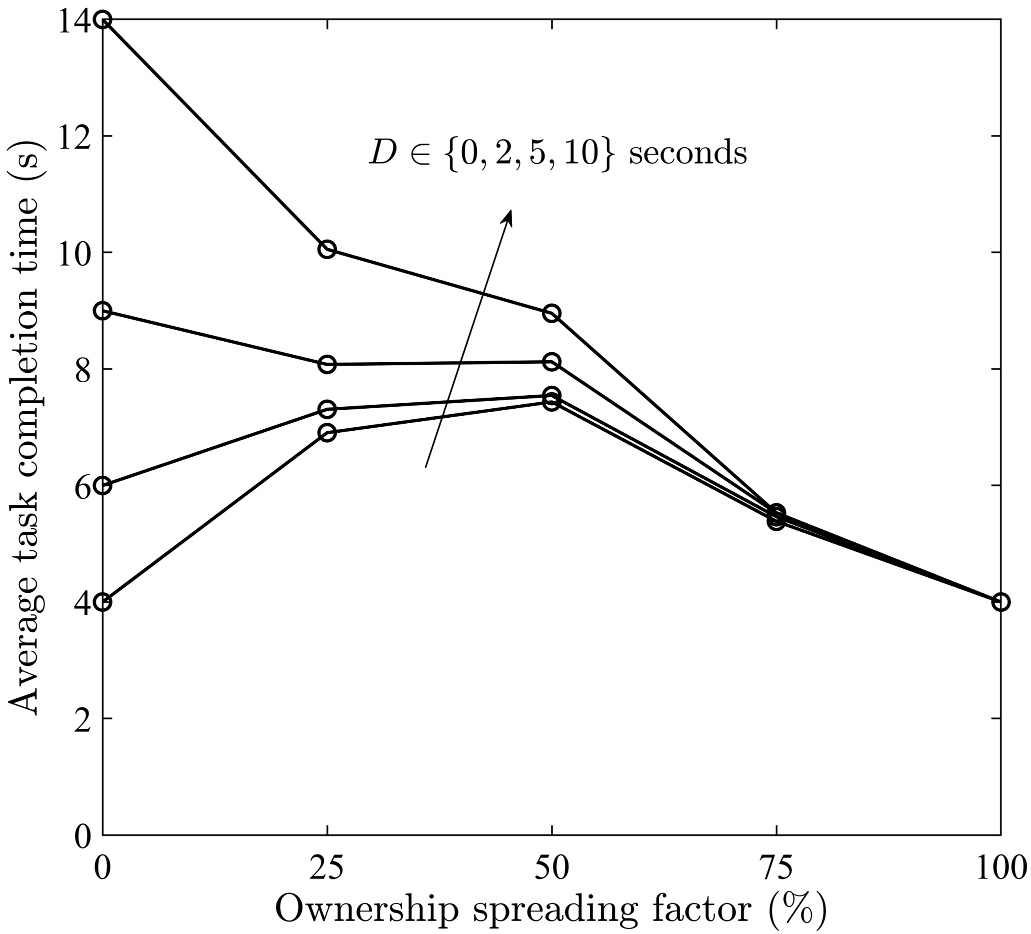
Spreading Ownership



Minimizing completion time of physical tasks by spreading ownership of robots across MUs

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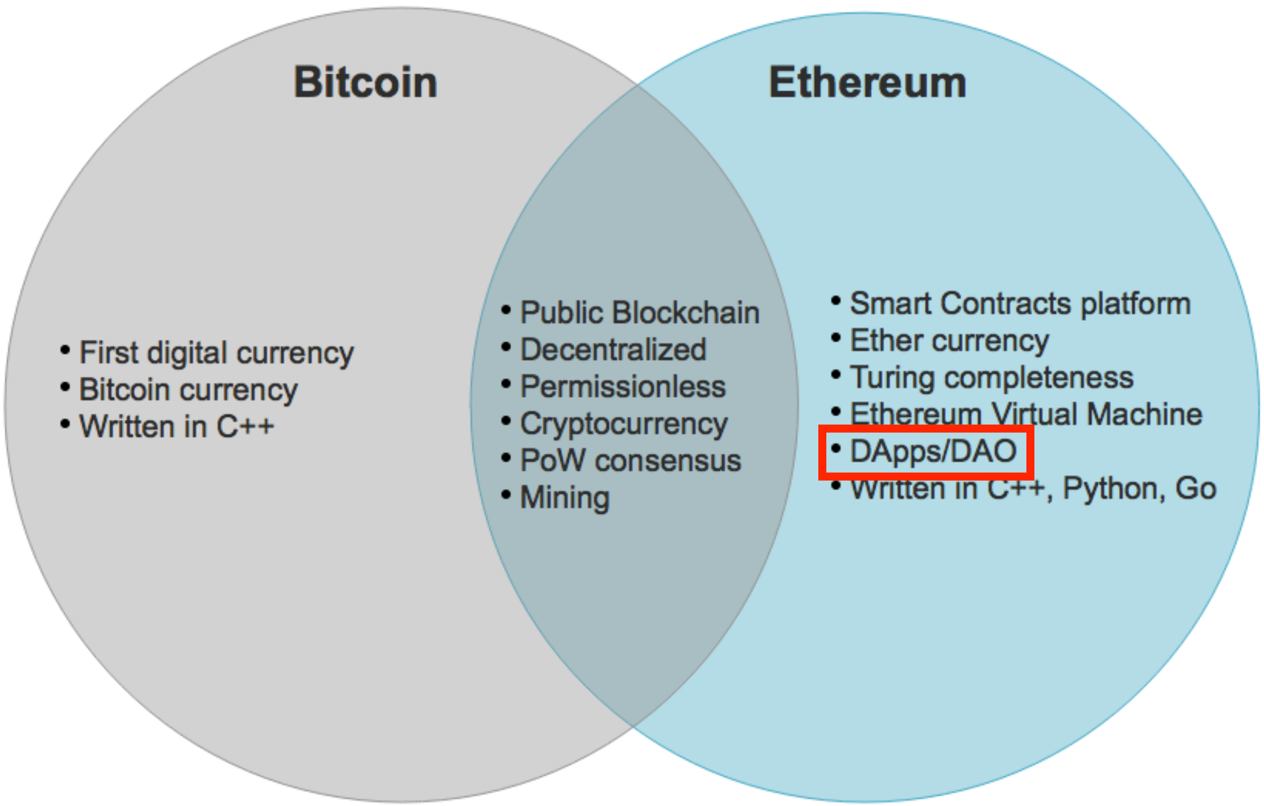
Decentralization



Decentralized blockchain technologies used to realize blockchain IoT (B-IoT)

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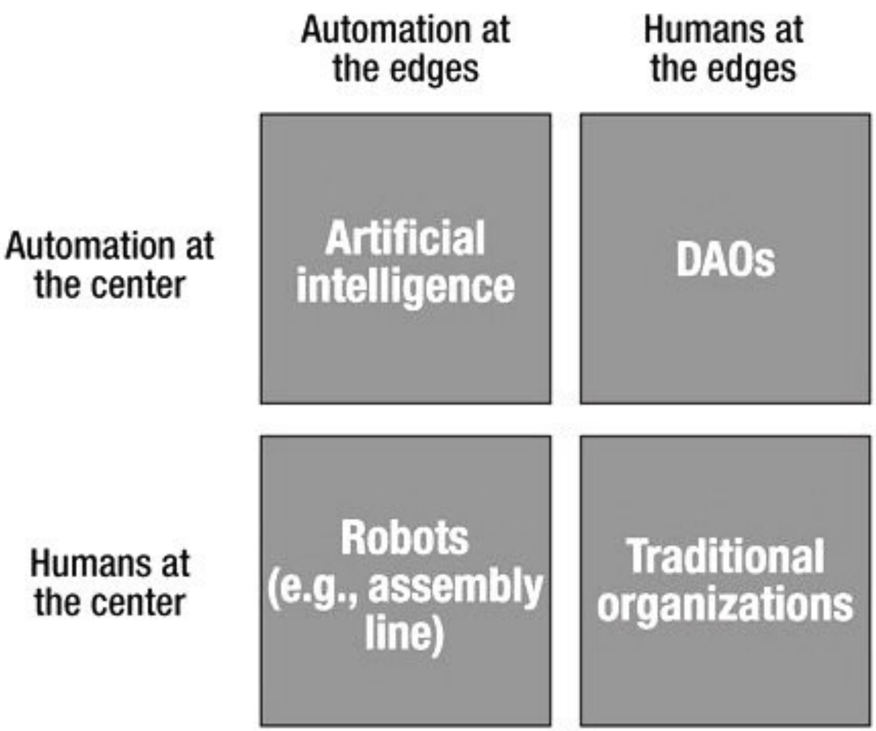
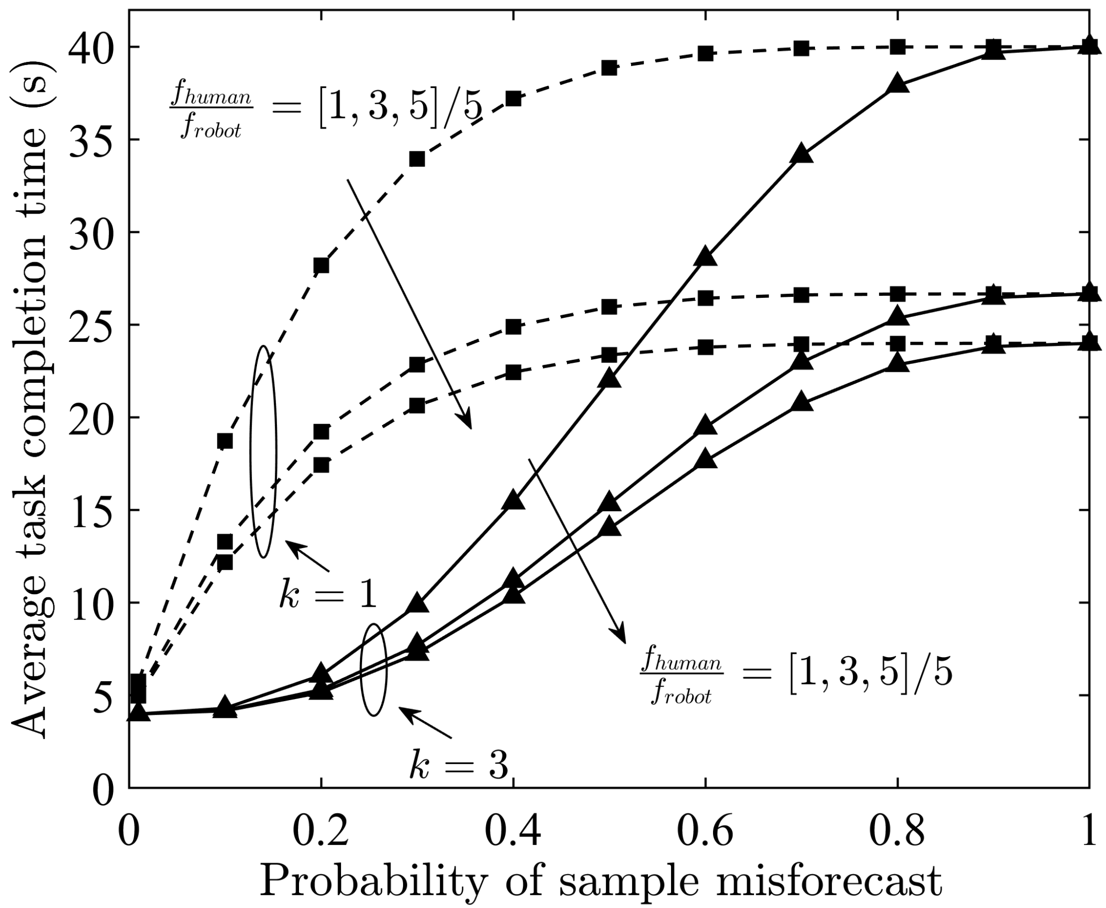
Ethereum: DAOs vs. AI & Robots



Decentralized Autonomous Organizations (DAOs)

- Salient feature of Ethereum
- Open-source, distributed software that executes smart contracts
- Unlike autonomous AI based agents, DAOs by design heavily rely on involvement from humans at the edges (“crowdsourcing”)

Decentralizing the Tactile Internet



Smart Contracts
- Help establish/ maintain trusted HART membership

Crowdsourcing
- Nearby HOs help finalize physical tasks when *k* haptic feedback samples are misforecast

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maier@ieee.org