Interplay Between Wireless Communications and AI Computing

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AI, AI, and AI
ML, ML, and ML

Yes! Are we going to talk AI/ML in communication systems and networks toward 6G?

A sort of, but not exactly as you expect …

Slight Gossip

- September 1989, precisely 30 years ago, a young person, after getting his PhD, was moving to New York to migrate his industrial and research career from satellite mobile communications (Communication Satellite Corp.) to wireless data networks (IBM T.J. Watson Research Center)
- His PhD dissertation is about synchronization, a subject considered “very traditional research” in communication at that time
- Yes, this young person is KC
- What exactly happened in these 30 years?

1989-2019

1989-2019

1989-2019


Roku
My Feed
TV Shows
News
Search
Streaming Channels
Settings
NETFLIX
hulu
VUDU
HBO NOW
amazon
sling
CRACKLE
PANDORA

1989-2019


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Microsoft Windows/286
Version 2.11
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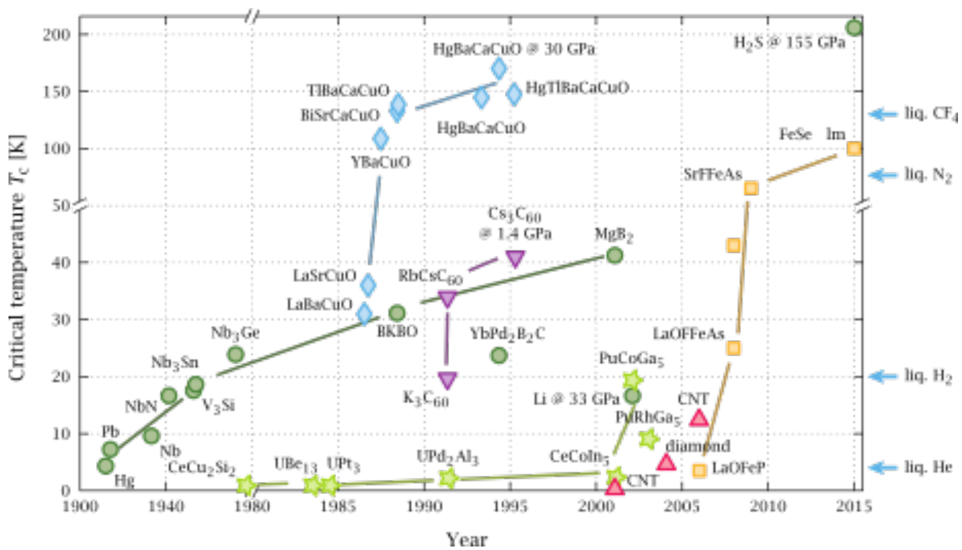
iOS 13

1989-2019

GPU for
Deep Learning

1989-2019 (Physics)



1989-2019 (Cancer Therapy)

1981 – American Dr. Bernard Fisher proves lumpectomy is as effective as mastectomy for breast cancer[4]

1989 – US FDA approves Carboplatin, a derivative of cisplatin, for chemotherapy[10]

1990 – US FDA approves tamoxifen for major additional use to help prevent the recurrence of cancer in "node-negative" patients[28]

From Wikipedia

Precision Medicine

1989-2019 (2G – 5G)

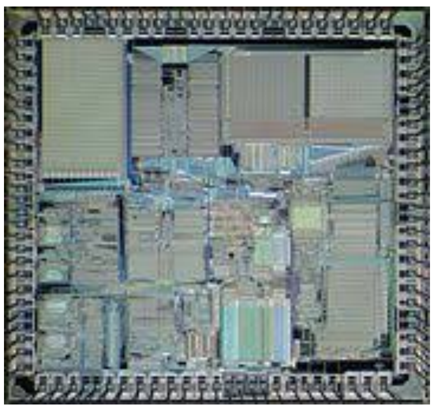
Title

Development of CDMA for Cellular Communications, 1989

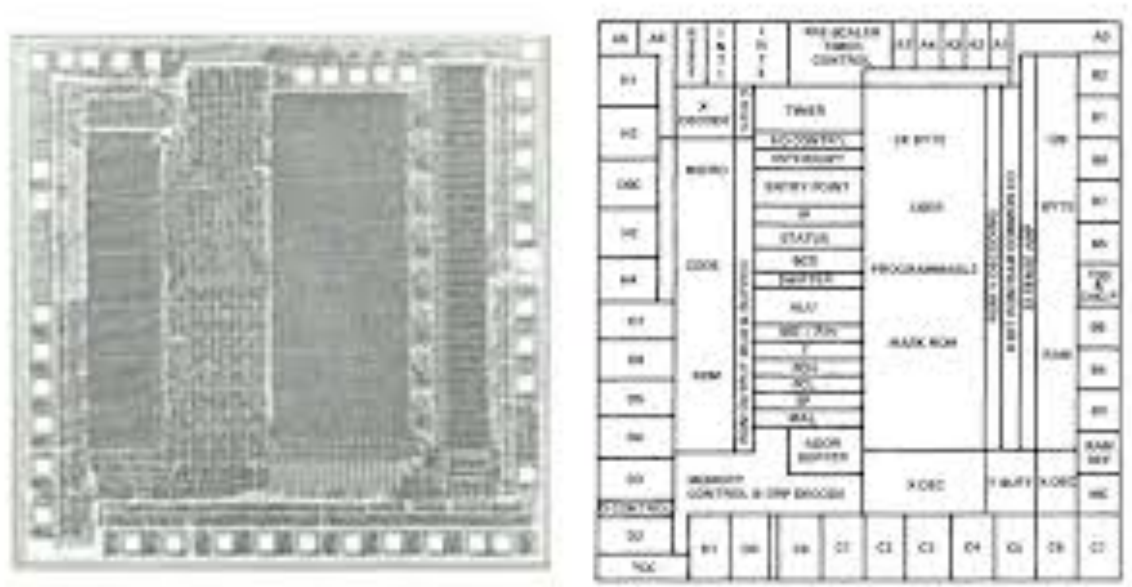
Citation

On 7 November 1989, Qualcomm publicly demonstrated a digital cellular radio system based on Code Division Multiple Access (CDMA) spread spectrum technology, which increased capacity, improved service quality, and extended battery life. This formed the basis for IS-95 second-generation standards and third-generation broadband standards that were applied to cellular mobile devices worldwide.

1989-2019



Motorola DSP 56000



TI DSP

Semiconductor industry growing as Moore’s law drives advances in communications & networking

The shown photo is Apply A12 Bionic Processor using TSMC 7nm IC fabrication (10B gates), while quantum limit for silicon IC fabrication is not far away.

It is inappropriate to ignore computational complexity (i.e. energy) in ML/AI algorithms and systems.

Tiny Vision by Looking into History

- What happened after WW II
  - Claud Shannon's Information Theory
  - Von Neuman's Game Theory and invention of Computer
    - The concept of utility and a priori probability in statistical decision theory
    - Yes, we are still using Von Neuman machine in modern computer architecture
  - A.N. Kolmogorov developed Probability Theory
- Late 1960's
  - Statistical Communication Theory was well established
  - Statistical Learning Theory was getting mature
  - Computers and Computer Networks going to be practical
  - Very soon, artificial intelligence would emerge beyond just concepts

Communication Technology Prior to 1980's: Synchronization as Illustration

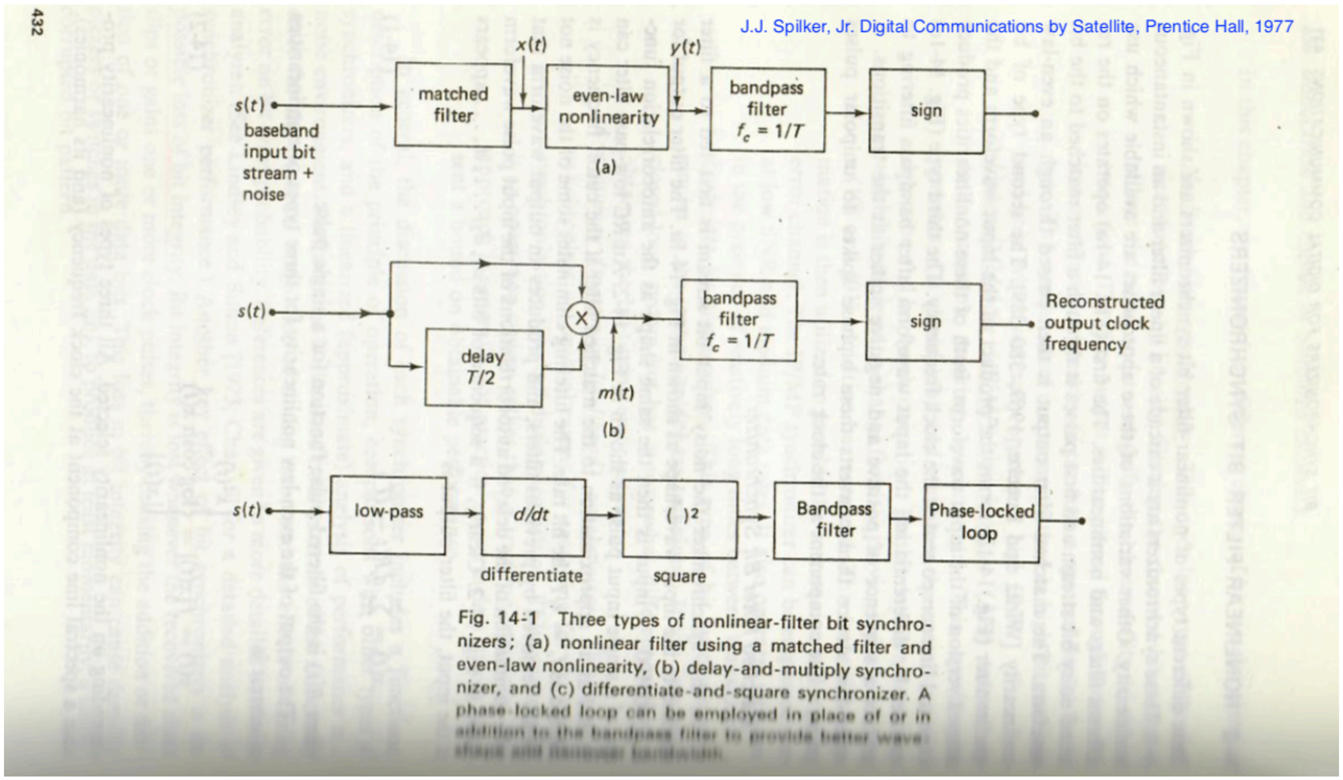


Fig. 14-1 Three types of nonlinear-filter bit synchronizers; (a) nonlinear filter using a matched filter and even-law nonlinearity, (b) delay-and-multiply synchronizer, and (c) differentiate-and-square synchronizer. A phase-locked loop can be employed in place of or in addition to the bandpass filter to provide better wave-shape and [illegible] bandwidth.

A Silent Communication Technology Advance in 1980's

IEEE TRANSACTIONS ON INFORMATION THEORY, VOL. IT-29, NO. 4, JULY 1983 543

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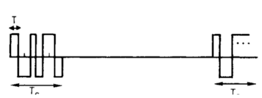
Nonlinear Estimation of PSK-Modulated Carrier Phase with Application to Burst Digital Transmission

ANDREW J. VITERBI, FELLOW, IEEE, AND AUDREY M. VITERBI, MEMBER, IEEE

Abstract—Burst transmission of digital data and voice has become commonplace, particularly in satellite communication systems employing time-division multiple-access (TDMA) and packet demand-assignment multiple-access (DAMA) techniques. In TDMA systems particularly, phase estimation on each successive burst is a requirement, while bit timing and



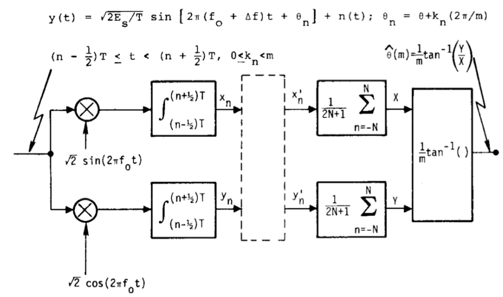


Fig. 2. Basic phase estimator for *m*-PSK carriers.

Computing digitized samples, rather than analog processing, enables digital communication and networks and advances with computing and semiconductor technology.

BTY, do not forget who made the critical contribution to the analysis of analog PLLs.

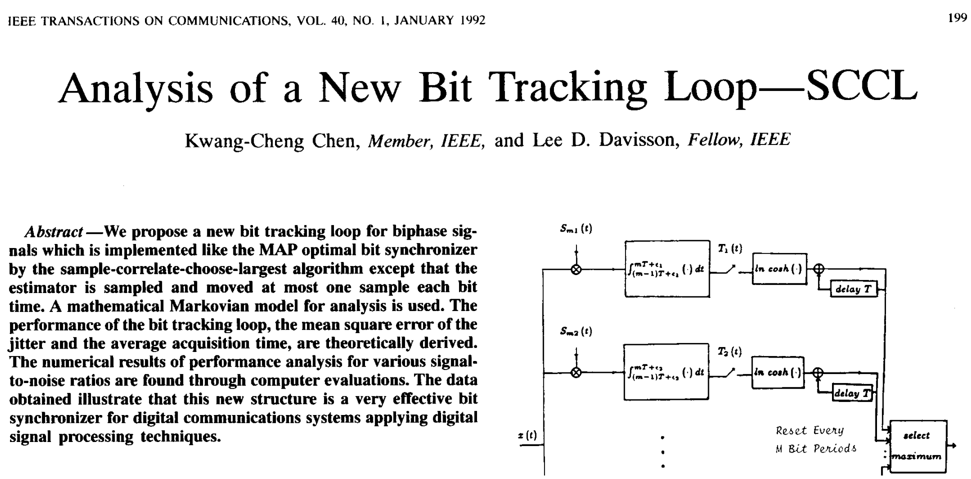
1989-2019

- The design of INMARSAT receiver in 1989 had
  - One CPU handles multiple access communication
  - Two Digital Signal Processors to calculate physical layer operations
  - One co-processor dedicated to decoding FEC
- Total four processors inside a receiver, more complicated than almost computers at that time
- State-of-the-art communication inside a handset requires
  - One DSP to handle physical layer
  - One co-processor for coding and decoding
    - 2000, KC's undergraduate students developed a co-processor for TI-C6x DSP to implement adaptive OFDM
  - One multi-core CPU to handle protocol stack for layers 1-4
  - One multi-core Application Processor with ANN
- Surely, many processors and antennas for different purpose

Computer architecture is critically important in communications

L.-F. Wei, the laureate of the Best Paper in 1989 IEEE Information Theory Society, in a private discussion

Back to KC's PhD Research

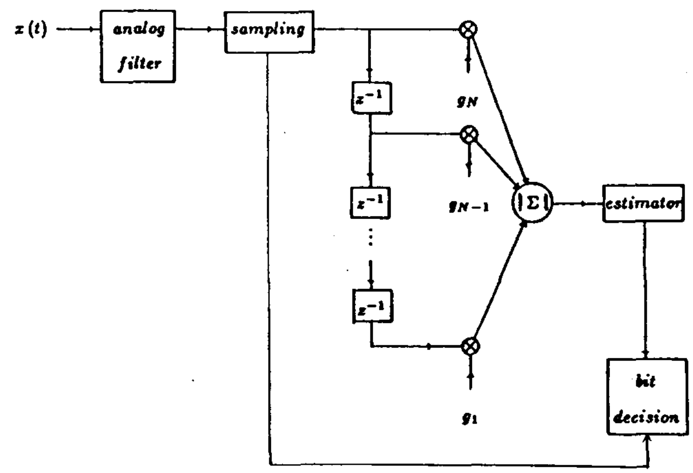


IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. 40, NO. 1, JANUARY 1992 199

Analysis of a New Bit Tracking Loop—SCCL

Kwang-Cheng Chen, *Member, IEEE,* and Lee D. Davisson, *Fellow, IEEE*

Abstract—We propose a new bit tracking loop for biphase signals which is implemented like the MAP optimal bit synchronizer by the sample-correlate-choose-largest algorithm except that the estimator is sampled and moved at most one sample each bit time. A mathematical Markovian model for analysis is used. The performance of the bit tracking loop, the mean square error of the jitter and the average acquisition time, are theoretically derived. The numerical results of performance analysis for various signal-to-noise ratios are found through computer evaluations. The data obtained illustrate that this new structure is a very effective bit synchronizer for digital communications systems applying digital signal processing techniques.



Online and model-free computation of digital samples to make **automated decisions** for synchronization!

It sounds like machine learning for communications!

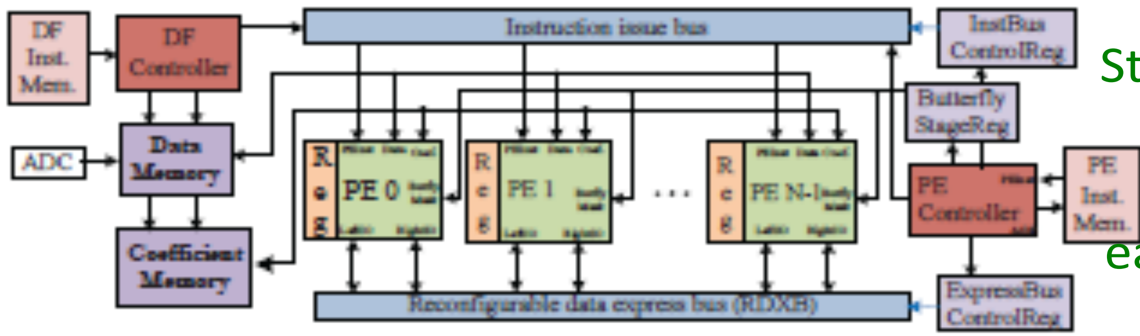
A View Regarding ML or AI in Communications and Networking

- If the system model is available and time-static, please use optimization that has become mature in past decades
    - In terms of convergence and computational complexity
- The principle to develop the online algorithm

  New_Estimate $\leftarrow$ Old_Estimate + Step_Size [Target − Old_Estimate]

- The key aspects of ML
    - Automated decisions/actions
    - Online, with possible assistance of offline computations
    - Model-free or at least uncertainty in the model(s)
    - Usually time dynamic
        - Only a small fraction of ML algorithms have been mathematically proven about convergence behavior

Computationally Efficient Architecture

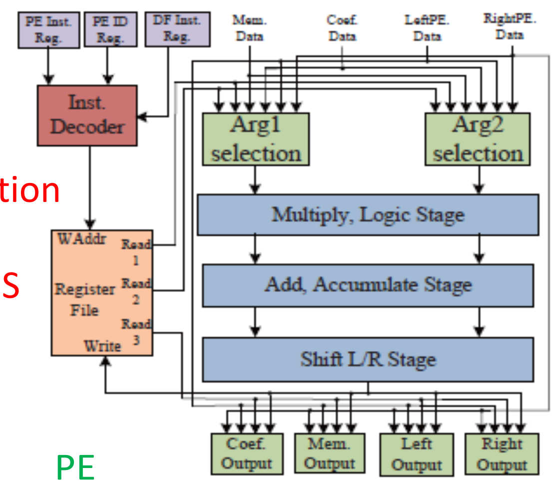


Strike between power and efficiency, of scalability and easy programmability

[Liang and Chen, IEEE PIMRC, 2010]

Types	Instruction	Arguments
Word processing	ADD	R/C, dst, src1, src2, S
	SUB	R/C, dst, src1, src2, S
	MUL	R/C, dst, src1, src2, S
	MAC	R/C, dst, src1, src2, S
	MSUB	R/C, dst, src1, src2, S
	BUTFLY	R/C, dst, src1, src2, S
	DIST	R/C, dst, src1, src2, S
Bit processing	AND	dst, src1, src2
	OR	dst, src1, src2
	XOR	dst, src1, src2
Comparison	COMPARE	dst, src1, src2
	DEMAP	dst, src1, src2
Single operand	SQUARE	R/C, dst, src, I
	STORE	R/C, dst, src, I
Controling	W_REG	dst, I
	INC_REG	dst, I
	BRANCH	dst, src
	NOP	

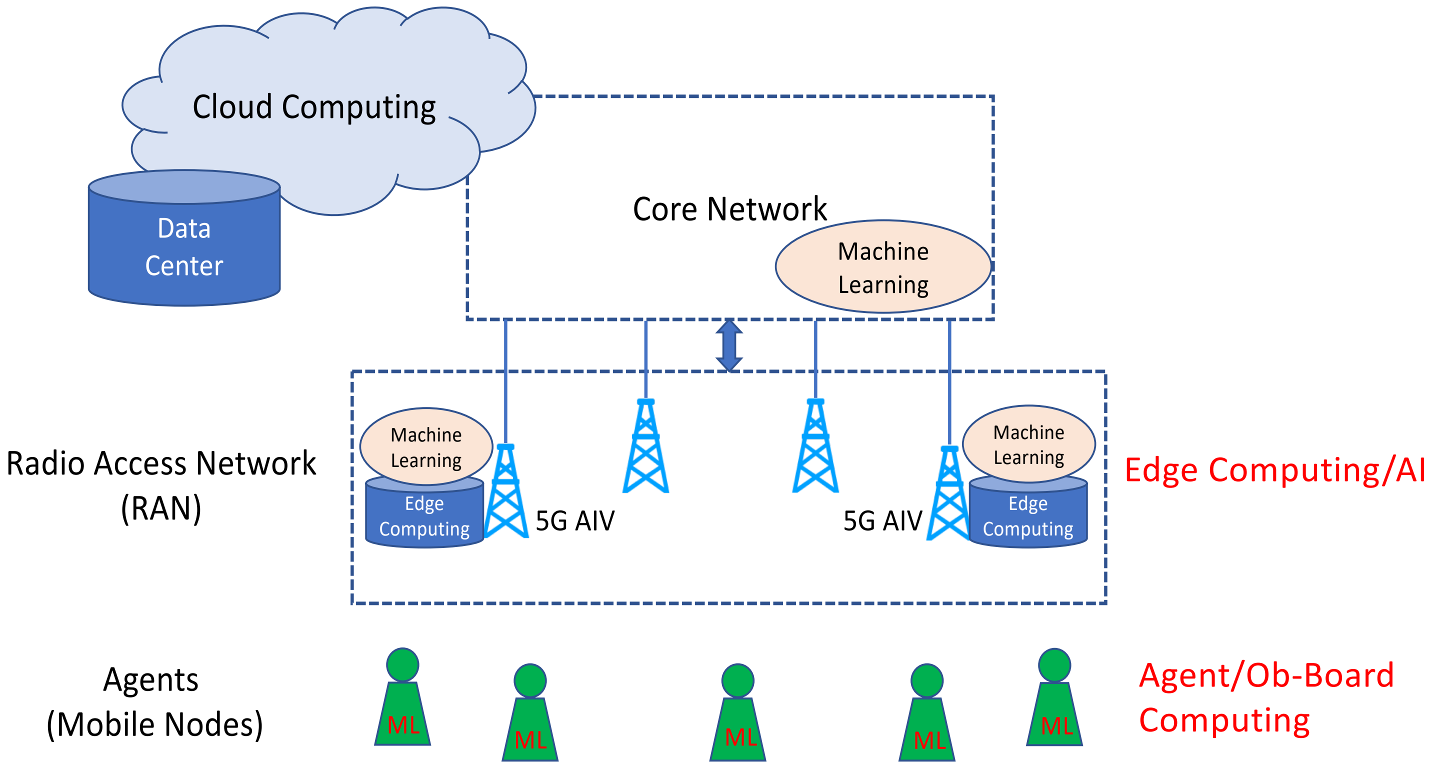
Simple instruction set & no complicated OS



PE

Highly Parallel & Scalable Architecture

Holistic View of Computing and Networking



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Existing Examples of ML to Wireless

- Channel State Estimation: Channel state information is critical to air-interface technology, which has been considered to be inferred/estimated with the aid of deep learning.
- User Behavior: User behavior such as mobility patterns can be useful to network management functionalities and mobility management, through big data analysis by ML.
- Traffic Prediction: Deep packet inspection, network intelligence, and user mobility patterns, can be used to predict (wired/wireless) network traffic, for more efficient network/radio resource allocation
- Anticipatory Mobility Management: ML can enable AMM to eMBB, mMTC, and uRLLC service scenarios in the mobile networks.
- Network Security: ML might be one of the most attractive tools to enhance network security, detect attacks and intrusions to networks.

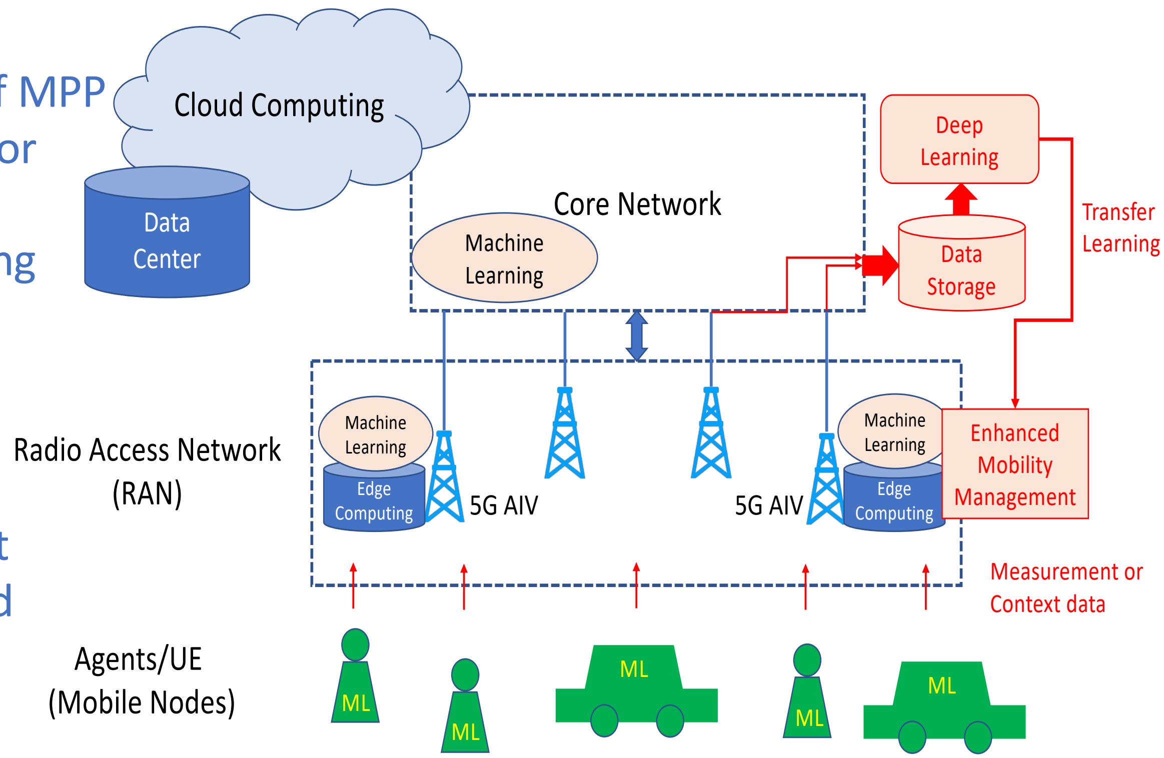
Potential Role of ML in Mobile Networking

	eMBB (service-oriented)	mMTC (data oriented)	uRLLC (physical delivery)
Channel State Estimation	CN & RAN (online)		RAN (online)
User Behavior	CN		RAN (online)
Traffic Prediction	CN (online) & RAN (online)	CN	RAN (online)
Anticipatory Mobility Management	CN (online) & RAN (online)	CN	CN & RAN (online)
Network Security & Intrusion Detection	CN	CN	CN & RAN

Network Architecture of Offline Machine Learning (proposal to ITU-T)

Possible Realization of MPP with New Data Flows or Connections and New Networking/Computing Entities in Network Architecture
(in red lines/boxes)

Offline ML means that ML is not directly used for online network functionalities.



Issues to deploy machine learning for future network architecture

- What is the network functionality with performance requirements?
- What kind of data?
- What type of machine learning to satisfy the target network functionality?
- Where to compute? agent/edge/cloud? appropriate networking to support?
- How to collect data? (also data cleaning)
- How to send the collected data to computing or storage?
- How does the machine learning assist/enhance/enable network functionality?
- How does the convergence behavior of machine learning align with the performance requirements of target network functionality?

Issues to deploy machine learning for future network architecture

- What is the network functionality with perform... nce requirements?
- What kind of data?
- What type of m... learni... ...get... ...ork functionality?
- Where to comp... ...g to supp...
- How to co...
- Ho...
- How do... ...nable network fu... ...
- How does the c... ...vergence behavior of machine learning align with the performance requirements of target network functionality?

It is NOT as simple as orchestration in logic!

Engineers know the fact that AI is not as smart people think.

Due to computing time, energy, and application-specific design.

Communications of ACM, Feb. 2019

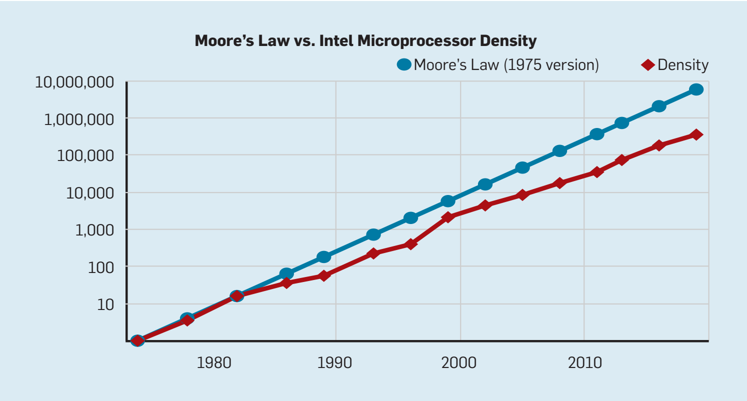
turing lecture

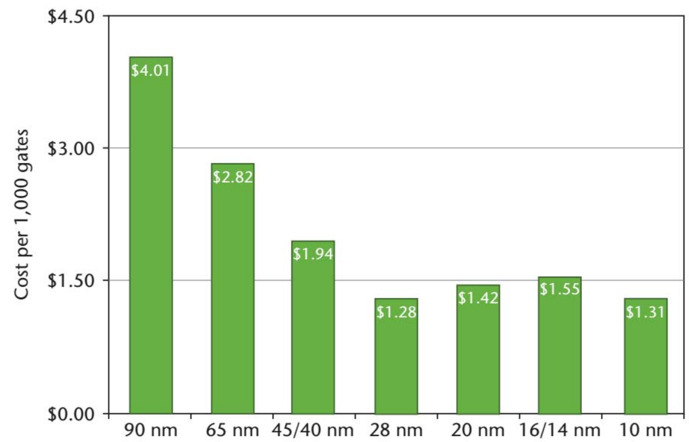
DOI:10.1145/3282307

Innovations like domain-specific hardware, enhanced security, open instruction sets, and agile chip development will lead the way.

BY JOHN L. HENNESSY AND DAVID A. PATTERSON

A New Golden Age for Computer Architecture





However, do not forget another fact!

Quantum Limit is in sight

TSMC is constructing foundry at 3nm!

3nm is roughly the size of 4 atoms!

AI computing can not rely on Morse' Law! Therefore, is relying on SW orchestration to advance wireless network architecture convincible?

Deeper Thought

- What is the energy for AlphaGO to play a game?
- What is the energy for a human champion to play a game?
- This is not a fair game at all, and thus do not be confused by the fantasy.
- We need a proper way to apply AI and ML into wireless.

Simplicity is the solution for network architecture due to latency and energy

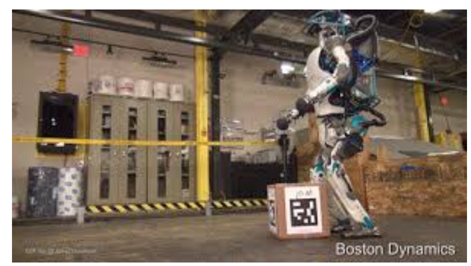
Particularly, AI/ML for (wireless) communications!

Human Intelligence

Rise of Smart Machines

Are you still making phone calls?

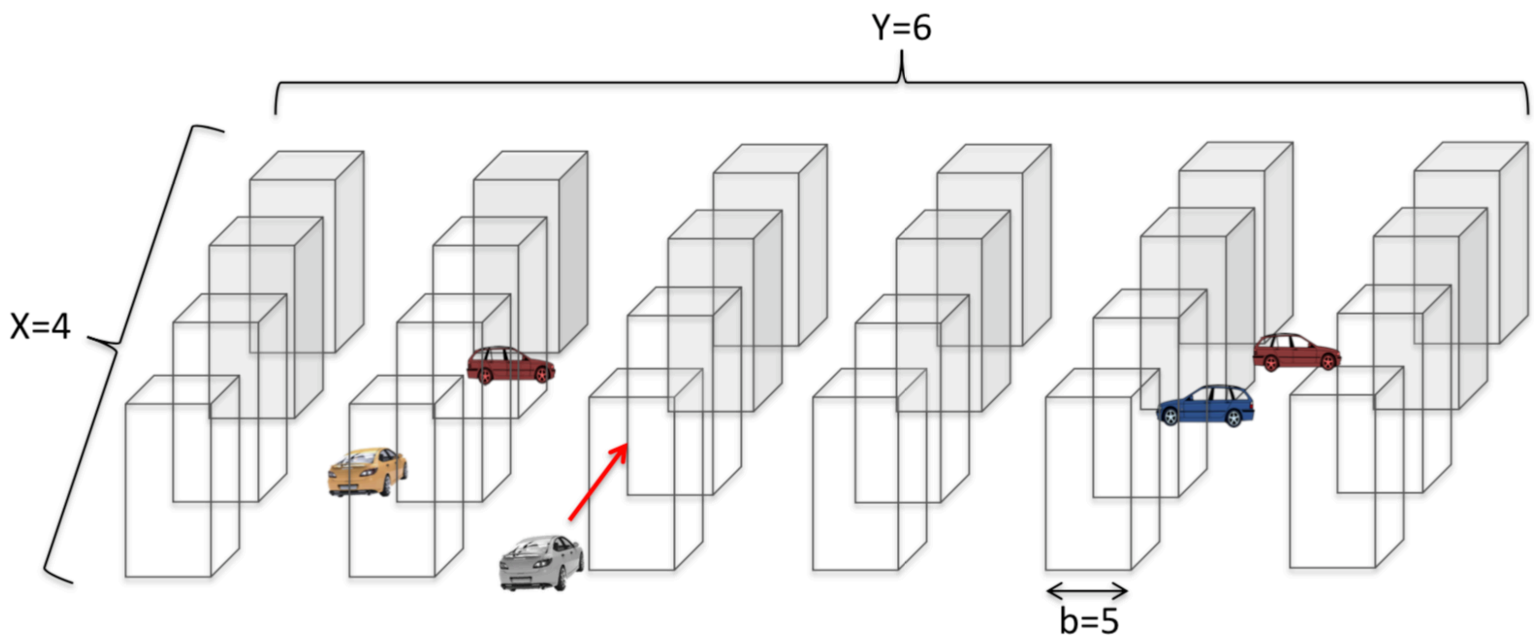
What do machines want for communication?



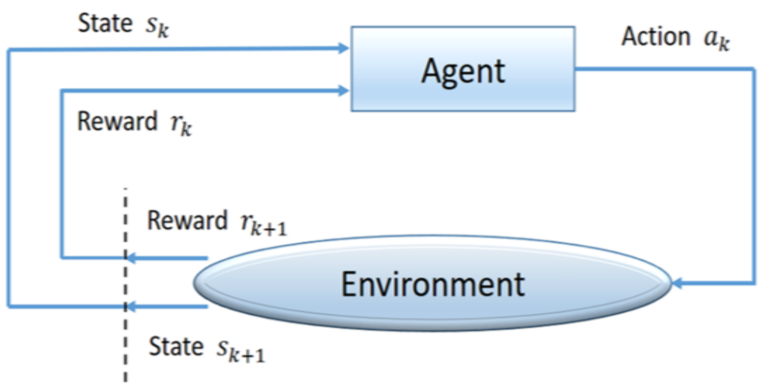
Networked Artificial Intelligence

More illustrations

A Toy Model for AVs over Manhattan Streets

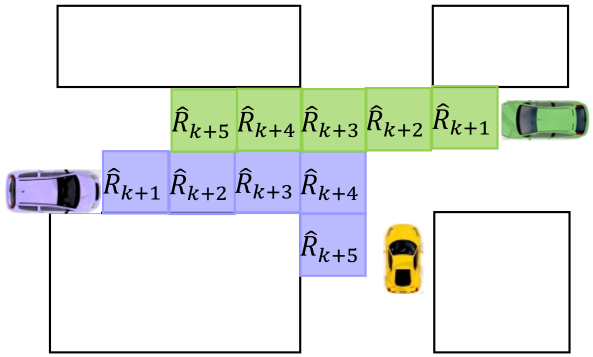


Reinforcement Learning



- The agent implements a mapping from states to probabilities of selecting each possible action
- This mapping is called the agent's policy and is denoted π_k, where $\pi_k(a|s)$ is the probability that $a_k = \text{a}$ if $s_k = s$
- **The agent's goal is to maximize the total amount of reward it receives over the long run**

Without Communication



- At time k, the agent recognizes other vehicle and generates reward map $R_{i,k}$
- For $k+d$ $(d = 1, \ldots, D, D$ is the depth of horizon) will be the expected reward map $\hat{R}_{k+d}$

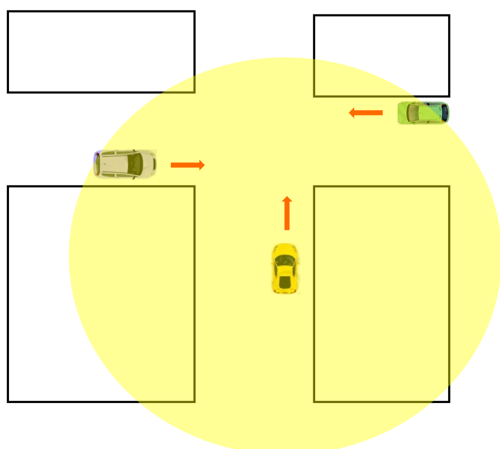
$$\hat{R}_{i,k+d} = [\hat{r}_{s_{k+d}}]$$

$$\mathbb{R}_{i,k:k+D} = \{R_{i,k}, \hat{R}_{i,k+1}, \ldots, \hat{R}_{k+D}\}$$

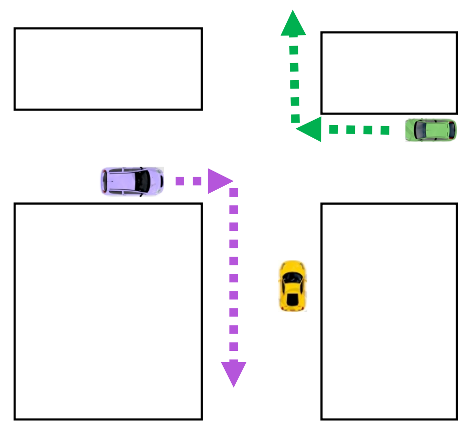
The agent makes decision based on $\mathbb{R}_{i,k:k+D}$

Ideal V2V Communication

- Assuming cars can communicate with each other within the communication range r
- In the simple scenario of V2V, cars will have two kind of additional information

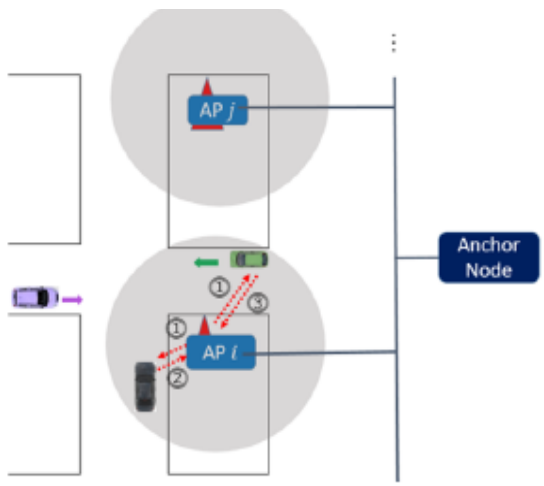


Within the communication range r, the yellow car will recognize the other cars' positions



The yellow car will get the information about other cars' movement (directions)

Ideal V2I2V Communication



- The network infrastructure (NI) relays the reward maps $\mathbb{R}_{AP_m,k:k+D}$ through APs $m \in M$

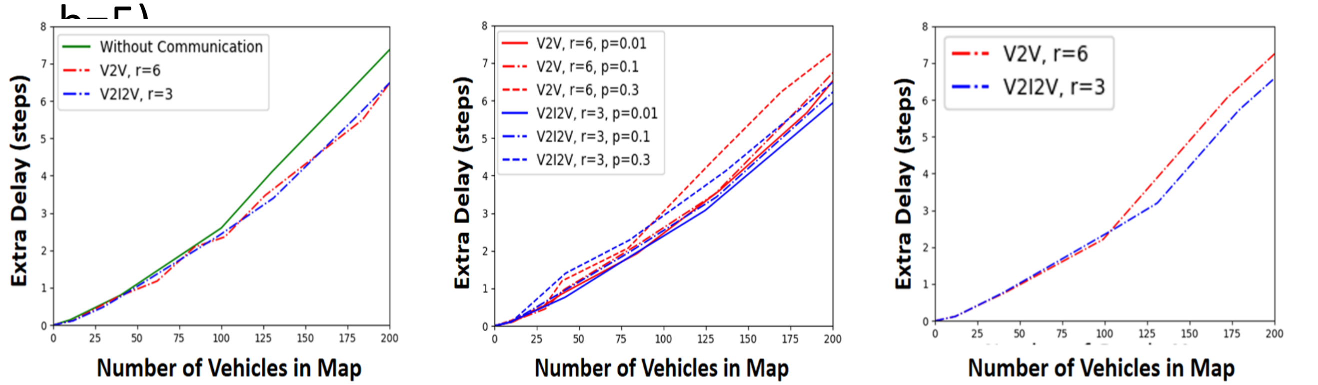
$$\mathbb{R}_{AP_{m,k:k+D}} \leftarrow \bigcup_{i \in \mathbb{M}_k} \mathbb{R}_{i,k:k+D}$$

$$\mathbb{R}_{NI_{k:k+D}} \leftarrow \bigcup_{m \in M} \mathbb{R}_{AP_{m,k:k+D}}$$

$$\mathbb{R}_{i,k:k+D} \leftarrow \mathbb{R}_{AP_{m,k:k+D}} \leftarrow \mathbb{R}_{NI_{k:k+D}}$$

Communication Enhances Multi-Agent Systems:
New Frontier of AI Computing

- Manhattan Model Street (M=4, N=6, b=5)



(a) MAS of RL with Ideal Wireless Communication (b) Message Errors Degrade Performance of MAS (c) Multiple Access Communication by rt-ALOHA

Networked AI

Multiple Access of rt-ALOHA

Modification of slotted ALOHA is required to support RL, named as real-time ALOHA (rt-ALOHA) due to the nature of AI/ML

- Data is useless once passing the required networking or communication latency ➔ age of information

- When the channel is busy, the agent (i.e. AV) is ready to receive immediately
- When the channel is idle, the agent broadcasts the message, and ready for receiving from others immediately after transmission without any acknowledgement by the receiving agent(s)
- There is no retransmission and thus backlogging

Lessons

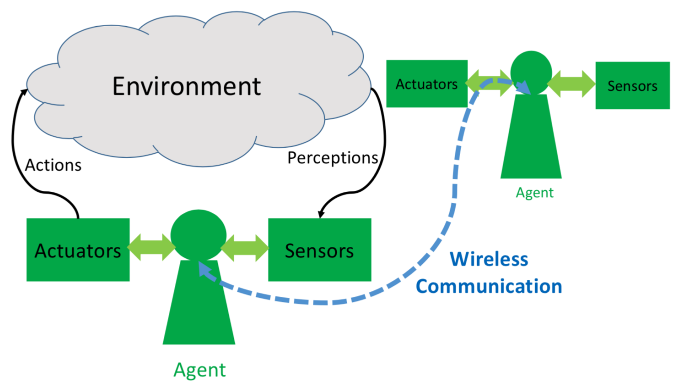
- We observe the how the communication well assists RL, that is, networked artificial intelligence
  - V2I2V communication better assists RL with small communication range, than V2V communication
  - Multiple access consideration suggests small cells.
- Real-time (i.e. low-latency) multiple access is more desirable in communication for AI
  - **Age of information** exchanged in robotic communications is a critical factor.
- **A correctly received message of latency larger than required value in ML is useless in AI.**
  - **Fundamentally different from H2H communication.**

Wireless robotic communications

Collaborative multi-agent systems [IEEE ICC 2019]

Networked Multi-Agent Systems

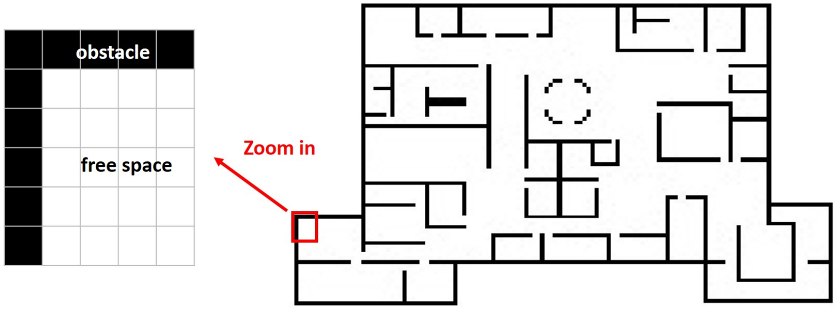
- AI/ML for communications emerges as a new technological frontier.
- However, the impacts of wireless communication on multiple AI agents/robots are rarely known.
  - Multiple AI agents forms a multi-agent system (MAS).
  - MAS of networking is a networked MAS.
  - Eisaku Ko and K.-C. Chen (IEEE GC’18) showed wireless communication enhances resource sharing MAS.
  - This is based on the investigations in collaborative MAS, widely applied in smart factory, autonomous vehicles, etc. [K.-C. Chen, H.-M. Hung, IEEE ICC’19]



Robots (Agents) of Wireless Communication Capability

Wireless Robotic Communications

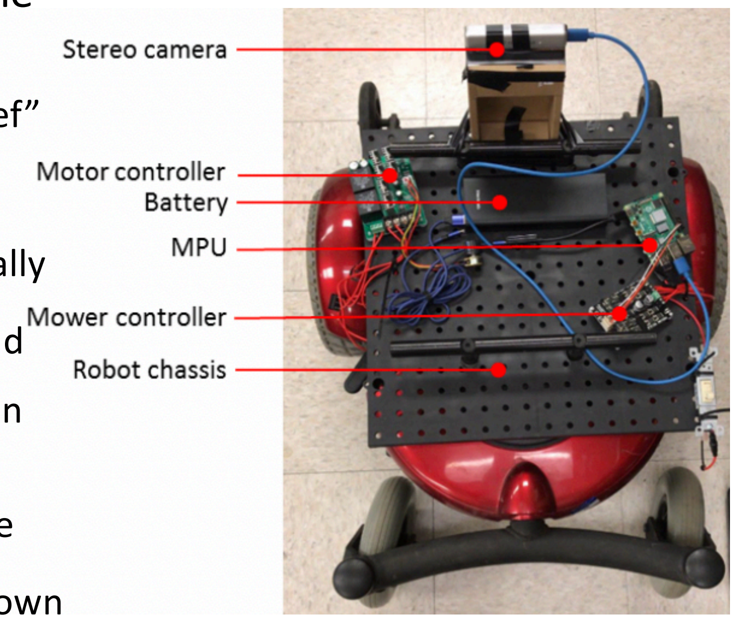
- One of the most critical application scenarios is collaborative robots working together toward a common mission in distributed computing
  - Collaborative MAS
  - Smart factory, service robots, etc.
- Goal: To comprehend the role of wireless robotic communication in collaborative MAS
  - Collaborative robots to clean the floor as right hand layout, without knowing the floor layout
  - Planning and localization algorithms are required



Toy Example: Floor plan of the cleaning area, where the area consists of 6760 free space grids and 1227 obstacle grids

Challenges in Wireless Robotics

- Any (mobile) robot suffers from a technical challenge of localization (or robot pose) problem to navigate (online learning) the environment
  - A robot must rely on sensors (in the environments or on-board) to understand the environment, to form the “belief” of its position (or pose), which is known as the private reference (i.e. coordinate system).
  - Private reference is expected to align with the public reference (i.e. environment coordinate system), but actually not.
  - Wireless techniques, such as wireless sensor networks and wireless localization, are required for robot navigation or operation, potentially with multi-modal fusion using vision sensors.
  - Consequently, extra knowledge inference and planning algorithms (offline learning) are required to work with the machine learning mechanism for actions.
  - A mobile robot prototype (automatic lawn mowing) is shown
    - Main actions for the robot is to install learning mechanism to determine actions of navigation.



Multiple Access: *p*-persistent rt-ALOHA

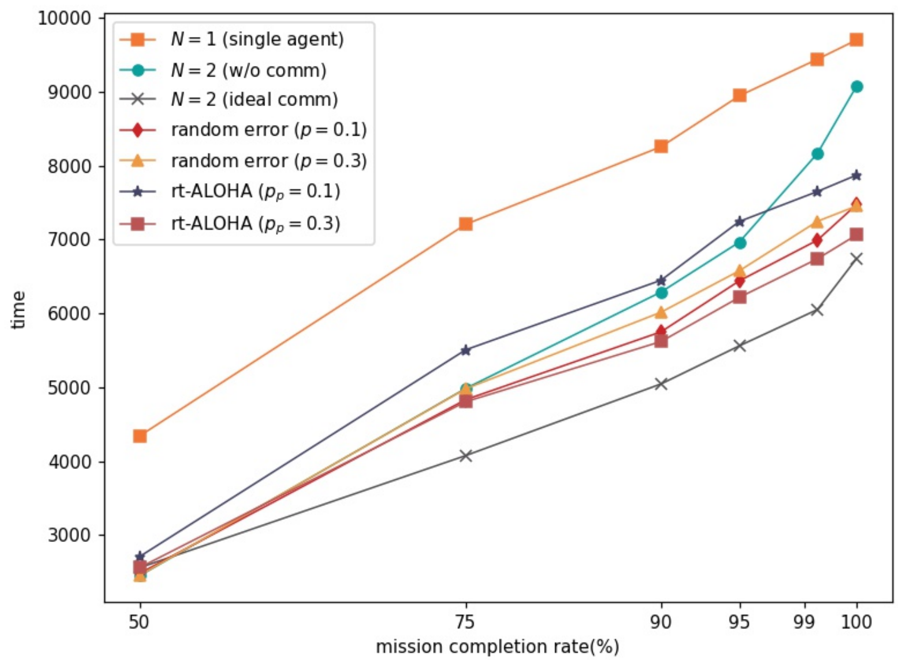
Latency is so critical for information exchange among collaborative agents to suggest real-time ALOHA

- When the channel is busy, the agent (i.e. cleaning robot) is ready to receive immediately.
- When the channel is idle, the agent broadcasts the message of desirable content, then immediately turns ready to receive from others right after transmission without any acknowledgement.
- There is no retransmission and thus backlogging.

Borrowing the concept from CSMA

- Proactive: if the agent senses other agents are within its communication range and the channel is not busy, agent broadcasts messages with probability p_p.
- Reactive: When the multi-access channel is busy, the agent stays at the reactive mode, ready to receive other's broadcast. When agent senses other agents are within its communication range, agent stays at the reactive mode with probability $1 - p_p$.

Wireless Communications Greatly Enhances Collective Performance of Collaborative Agents (MAS)



Technology Focus in M2M Communications: Massive Access (mMTC in 5G)

RECENT PROGRESS IN MACHINE-TO-MACHINE COMMUNICATIONS

Toward Ubiquitous Massive Accesses in 3GPP Machine-to-Machine Communications

Shao-Yu Lien and Kwang-Cheng Chen, National Taiwan University
Yonghua Lin, IBM Research Division

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Machine-to-machine communications: Technologies and challenges

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Fundamental Issues in M2M Communications 2.0

- What to communicate (i.e. traffic)?
  - Reward map and policy
  - 10 msec (i.e. 100 times of control in a second)
  - Age of information is critical, which means not only delay but also latency is critical
  - Sensor data collection and fusion
- How to communication?
  - Multiple access and heterogeneity
  - Scalability
  - Reliability
- M2M communications to facilitate AI computing, that is, Communications for AI

A new approach toward uRLLC in vehicular networking, different from what we get used in past 50 years

ACCEPTED FROM OPEN CALL

Ultra-Low Latency Mobile Networking

Kwang-Cheng Chen, Tao Zhang, Richard D. Gitlin, and Gerhard Fettweis

Abstract

Mobile networking to achieve the ultra-low latency goal of 1 msec enables massive operation of autonomous vehicles and other intelligent mobile machines, and emerges as one of the most critical technologies beyond 5G mobile communications and state-of-the-art vehicular networks. Introducing fog computing and proactive network association, realizing virtual cell by integrating open-loop radio transmission and error control, and innovating anticipatory mobility management through machine learning, opens a new avenue toward ultra-low latency mobile networking.

from computing scenarios, a new networking architecture has been identified, and then re-innovations of open-loop wireless communications beyond state-of-the-art low latency techniques have been introduced. The proposed approach integrates the idea of virtual cell for each AV, network virtualization, and proactive network association to reduce end-to-end networking latency toward 1 msec. Subsequent challenges in asynchronous multiple access can be resolved by multiuser detection (MUD). Finally, machine learning enabling anticipatory mobility management to serve proactive network association and open-loop wireless communications is shown to be effective. Such a

K.-C. Chen, T. Zhang, R.D. Gitlin, G. Fettweis, "Ultra-Low Latency Mobile Networking", *IEEE Network Magazine, March 2019*.

Two industries, computing and telecommunication, finally collides to form a new technological front!

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- Ad Hoc and Sensor Networks
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- Communication Software, Services & Multimedia Apps.
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- Signal Processing for Communications
- Wireless Communications
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- Selected Areas in Communications
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  - *Big Data*
  - *Cloud & Fog/Edge Computing, Networking and Storage*
  - *E-Health*
  - *Internet of Things & Smart Connected Communities*
  - *Machine Learning for Communications*
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1 September 2020

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