Intelligent Random Access for Next-Generation IoT Networks

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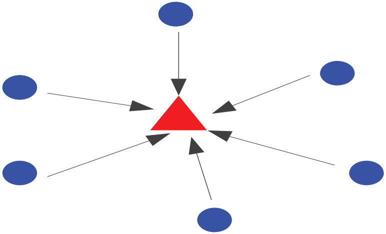
Outline

- Random Access: A Huge Gap between Theory and Practice
- A Unified Theory of Random Access: From the Queueing-Theoretical Perspective
- Learning-Based Random Access

Random Access: A Huge Gap between Theory and Practice

Multiple Access (MAC)



Multiple users transmit to a common receiver: How to share the resources?

- Centralized Access: A central controller performs resource allocation.
- Random Access: Each user determines when/how to access in a distributed manner.

Centralized Access

- Adopted in cellular systems since the first generation: Each Base Station (BS) allocates dedicated resources to users for data transmission.
- FDMA $\longrightarrow$ TDMA $\longrightarrow$ CDMA $\longrightarrow$ OFDMA
- Optimal resource allocation by BSs
- **Extensive signalling exchange between BSs and users**: Inefficient when the number of users is large and each with a small amount of data.

Random Access

- Adopted in both cellular and WiFi networks:
  - — Cellular in the licensed spectrum: signalling exchange
  - — Cellular in the unlicensed spectrum: data transmission
  - — WiFi: data transmission
- Performance degradation due to lack of coordination among users
- **Small overhead and scalable**: Increasing importance due to the paradigm shift from Human-to-Human (H2H) communications to Machine-to-Machine (M2M) communications.

M2M Communications

- M2M communications is expected to play a dominant role in the next-generation communication networks.
  - 40 billions machine-type devices to be connected by 2030
  - Wide applications of Internet-of-Things (IoT) in various domains such as smart grid, transportation, health care, manufacturing and monitoring
- Two out of three main services of 5G networks are for M2M communications: *massive Machine-Type Communications (mMTC) and Ultra-Reliable Low-Latency Communications (URLLC)*.
- Four out of six usage scenarios of 6G networks are related to M2M communications: *hyper reliable and low-latency communications, massive communications, ubiquitous connectivity, integrated sensing and communications, integrated AI and communications*.

Random Access for M2M Communications in IoT Networks

- A typical scenario of conventional H2H communications: A relatively small number of users each with a large amount of data to transmit

- M2M Communications:

  — massive number of devices

  — short packet payload

  — diverse and more stringent Quality-of-Service (QoS) requirements

- Random access is expected to play a dominant role in facilitating M2M communication in IoT networks.

- *Challenge: How to properly design random access schemes for M2M communications?*

Design of Random Access Networks: Three Key Questions

For each node:

- When to start a transmission?
- When to end the transmission?
- What if the transmission fails?

Question 1: When to Start a Transmission?

- Transmit if packets are awaiting in the queue.

  — Aloha [Abramson'1970]

- A more "polite" solution: Transmit if packets are awaiting in the queue **and the channel is sensed idle**.

  — Carrier Sense Multiple Access (CSMA) [Kleinrock&Tobagi'1975]

- Examples:

  — *Aloha-based*: Random access process of cellular networks (1G-5G) in the licensed spectrum

  — *CSMA-based*: Distributed Coordination Function (DCF) of WiFi networks, 5G New Radio Unlicensed (NR-U) in the unlicensed spectrum

Question 2: When to End the Transmission?

- Stop when the packet transmission is completed.
- Any "smarter" solution? **Stop when the transmission is deemed a failure**.
  - With full-duplex (i.e., able to receive signals during transmissions): Stop when other on-going transmissions are sensed.
  - With half-duplex (i.e., unable to receive signals during transmissions): Send a short request to reserve the channel first before the data packet transmission. **Connection (Grant)-based Access**
- Examples:

— *Connection-based*: 4-step Random Access-Small Data Transmission (RA-SDT) in 5G networks in the licensed spectrum, Request-To-Send/Clear-To-Send (RTS/CTS) access mechanism of DCF in WiFi networks

— *Connection-free*: 2-step RA-SDT in 5G networks in the licensed spectrum, basic access mechanism of DCF in WiFi networks

Question 3: What if the Transmission Fails?

- Inherent transmission failures caused by incoordination among transmitters.
- The definition of transmission failure depends on what type of receivers is adopted. Various assumptions on the receiver have been made, which can be broadly divided into three categories.
  - *Collision Model*: When more than one node transmit their packets simultaneously, a collision occurs and none of them can be successfully decoded. A packet transmission is successful only if **there are no concurrent transmissions**.
  - *Capture Model*: Each node's packet is decoded independently by treating others' as background noise. A packet can be successfully decoded as long as its **received signal-to-interference-plus-noise ratio (SINR) is above a certain threshold**.
  - *Joint-decoding*: **Multiple nodes' packets are jointly decoded**, e.g., Successive Interference Cancellation (SIC).

Question 3: What if the Transmission Fails?

- Resolving transmission failures: **Backoff**
  - Probability-based: Retransmit with a certain probability at each time slot.
  - Window-based: Choose a random value from a window and count down. Retransmit when the counter is zero.
- How to set the transmission probability?
  - **Adjust the transmission probability according to the number of transmission failures** i that the packet has experienced, i.e., $q_i = q_0 \cdot \mathcal{Q}(i)$, where $\mathcal{Q}(i)$ is an arbitrary monotonic non-increasing function of the number of transmission failures i, $i = 0, 1, ...$.
  - *Binary Exponential Backoff (BEB)*: $\mathcal{Q}(i) = 2^{-i}$.
    Adopted in DCF of WiFi networks and 5G NR-U.
    Constant Backoff: $\mathcal{Q}(i) = 1$.
    Adopted in the random access process of cellular systems in the licensed spectrum.

Design Degrees of Freedom of Random Access Networks

- Sensing-free (Aloha) or Sensing-based (CSMA)
- Connection-free or Connection-based
- Backoff: Constant, Exponential, ...
- ...

Performance Metrics of Random Access Networks

- **Network Throughput**: the average number of successfully decoded packets of the network per time slot.
- **Network Sum Rate**: the average number of successfully decoded information bits of the network per time slot.
- **Delay** of a packet
  - Access delay (service time): the time interval from the instant that it becomes the Head-of-Line (HOL) packet to its successful transmission.
  - Queueing delay (waiting time + service time): the time interval from the packets arrival to its successful transmission.
- **Stability**: A network is stable if all the nodes' queues are stable.
  - Queue-stability: A queue is defined as queue-stable if the steady-state distribution of its queue length exists.
  - Throughput-stability: A queue is defined as throughput-stable if its throughput is equal to the input rate.
- ......

Challenges for Random Access Design

- The network performance is sensitive to the setting of access parameters.
- When the number of users/devices increases, the network performance may drastically degrade due to a significant increase of transmission failures if the access parameters are not properly selected.
- To support **massive access** and **stringent QoS requirements** of M2M communications, the random access schemes need to be carefully designed, with the parameters optimally tuned. — *But how?*

Lack of a Unified Theory of Random Access

- Despite a long history and wide applications, the theory of random access is much less developed than centralized access, which has been the focus of the MAC theory.
- Multiuser information theory:
  - Assume a continuous **bit stream** for each user.
  - Determine the maximum information transmission/encoding rate of each user for reliable communications.
  - Require **coordination** among users' transmissions.
- For random access:
  - Users decide when/how to transmit in a **distributed** manner.
  - Each user has a buffer to store the incoming **packets**.
  - In addition to the maximum information transmission rate, performance metrics related to **data queues**, e.g., stability and delay, are also of central interest.

Fundamental Questions to be Answered

- **How to stabilize the network?**
  - How to determine the **stability region of input rates**, within which and only within which the network can be stabilized?
  - For given input rates within the stability region, how to properly choose the **transmission probabilities of nodes** to stabilize the network?
- **How to optimize the performance?**
  - How to maximize the network **throughput** by optimizing the transmission probabilities of nodes?
  - How to minimize the mean queueing **delay** by optimizing the transmission probabilities of nodes?
  - ......
- **What are the key factors and how would they affect the optimal performance?**
  - What are the effects of **sensing** on the optimal throughput/delay performance?
  - What are the effects of **backoff** functions on the optimal throughput/delay performance?
  - ......

Random Access from a Coding Perspective

- Aloha with advanced coding/decoding design
  - Coded Slotted Aloha (CRDSA [Casini,De Gaudenzi&del Rio Herrero'2007], IRSA [Liva'2011][Munari'2021], Frameless Aloha [Stefanovic,Popovski&Vukobratovic'2012], ...)

    — Assumptions: Time slots are grouped into frames. Each user transmits coded segments in multiple slots of each frame with a certain probability.

    — Objective: Maximize the network throughput.
  - Unsourced Multiple Access [Polyanskiy'2017], [Liva&Polyanskiy'2024]

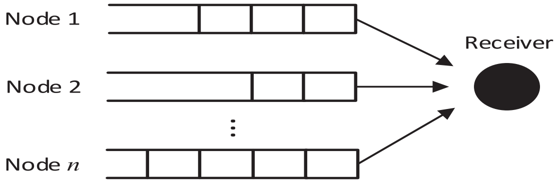
    — Assumptions: K_a out of K ($K \gg K_a$) users are actively transmitting and the receiver is unable to associate messages to users.

    — Objective: Minimize the per-user probability of error

- No consideration of data queues

Random Access from a Queueing Perspective

- Multiple access as a multi-queue-single-server system:

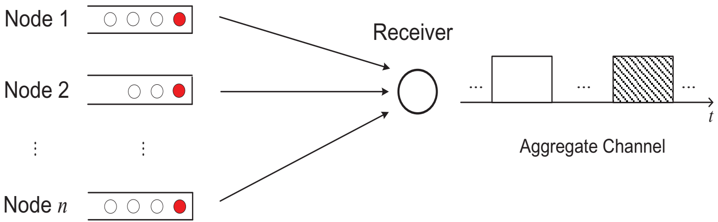


- Nodes have their own data arrivals and uncoordinated transmissions, but coupled service processes.

- How to characterize the coupled service processes?

Modeling of Random Access Networks

- Analytical models are usually customized for specific random access schemes to tackle specific problems.
- Modeling approaches can be broadly divided into two categories: **Channel-centric** and **Node-centric**, where the former focuses on modeling **the aggregate channel/traffic**, and the latter focuses on modeling **nodes' behavior**.



Channel-Centric Modeling

- Modeling focus: Aggregate traffic
- Representative models:
  - [Abramson'1970], [Kleinrock&Tobagi'1975]
    - Assume the aggregate traffic follows the Poisson distribution.
  - [Carleial&Hellman'1975], [Kleinrock&Lam'1975]
    - Model the dynamic change of the aggregate traffic
- Widely adopted in performance analysis of random access procedure in cellular networks.
- Capture the essence of contention among nodes and simplify the throughput analysis.
- **Ignore nodes' queues**.

Node-Centric Modeling

- Modeling focus: Nodes' queues
- Representative models:
  - [Tsybakov&Mikhailov'1979]
    - Model the queue lengths of n nodes as an n-dimensional Markov chain.
    - **Tractable only for two-node Aloha**.
  - [Rao&Ephremides'1988], [Szpankowski'1994] [Luo&Ephremides'1999], [Dimitriou&Pappas'2018]
    - Develop a hypothetical dominant system, where a node would send dummy packets when its queue is empty.
    - **Tractable only for two-node Aloha**.
    - **Approximations and bounds** for $n \geq 3$.

Node-Centric Modeling

- Modeling focus: Nodes' backoff process
- Representative models:
  - [Bianchi'2000]
    - Widely adopted in performance analysis of WiFi (**Symmetric CSMA+BEB**) networks.
    - Model the **backoff** behavior of each single node by a two-dimensional Markov chain.
    - Accurate characterization of network throughput and mean access delay of packets when all the nodes' queues are assumed to be saturated.
    - Nodes' states are only partially captured by the two-dimensional Markov chain – Difficult to be extended to the **unsaturated** condition.

Unsolved Issues

- How to characterize the coupled service processes when the queues are not all-saturated?
  - How to determine the stability region of input rates, only within which the network can be stabilized?
  - For given input rates within the stability region, how to tune the access parameters of nodes to stabilize the network?
  - How to optimize the delay performance?
  - ......
- **A unified framework based on which various performance metrics can be analyzed and optimized.**

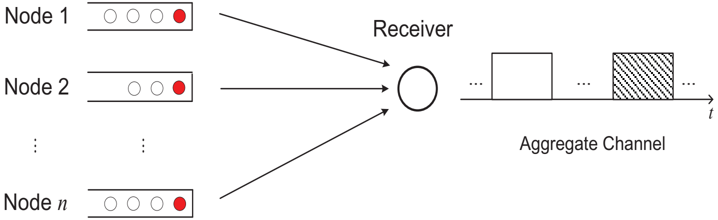
Unsolved Issues

- How to characterize the effects of key factors on the optimal performance?
  - To sense or not to sense: When is sensing beneficial?
  - Connection-based or connection-free: When is establishing a connection beneficial?
  - Constant backoff or exponential backoff: What backoff function is the best?
  - ......
- **A unified framework based on which various design features can be incorporated.**

A Unified Theory of Random Access: From the Queueing-Theoretical Perspective

Toward a Unified Analytical Framework for Random Access

- For modeling of a multi-queue-single-server system, the main challenge lies in characterization of the **coupled** service processes of queues.



- For each node's queue, the service process is determined by the aggregate activities of *all* **Head-Of-Line (HOL)** packets and how many of them can be successfully received. The former depends on the access/transmission strategy, and the latter depends on the receiver design.

Toward a Unified Analytical Framework for Random Access

- Key to characterization of coupled service processes of nodes' queues [Dai'12] [Dai'13] [Dai'22] [Dai'25]:
  - **Modeling HOL packets' behavior**: Discrete-time Markov renewal process
  - **Capturing the coupling of service processes**: Fixed-point equations of steady-state probabilities of successful transmission of HOL packets $\mathbf{p}$

L. Dai, "A theoretical framework for random access: Effects of carrier sensing on stability," *IEEE Trans. Commun.*, vol. 73, no. 1, pp. 275–291, Jan. 2025.

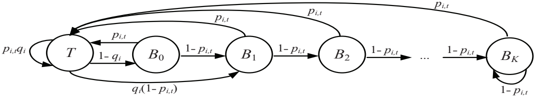
L. Dai, "A theoretical framework for random access: Stability regions and transmission control," *IEEE/ACM Trans. Networking*, vol. 30, no. 5, pp. 2173–2200, Oct. 2022.

L. Dai, "Toward a coherent theory of CSMA and Aloha," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3428–3444, Jul. 2013.

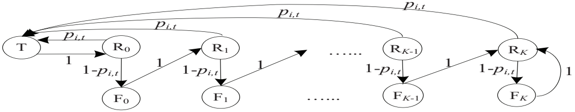
L. Dai, "Stability and delay analysis of buffered Aloha networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 2707–2719, Aug. 2012.

Modeling of HOL Packets

- HOL packets' behavior can be modeled as a discrete-time Markov renewal process $(\mathbf{X}_i, \mathbf{V}_i) = \{(X_{i,j}, V_{i,j}), j = 0, 1, \ldots\}$, $i \in \{1, 2, \ldots, n\}$:
  - The embedded Markov chain $\mathbf{X} = \{X_j\}$ **without Sensing**:



  - The embedded Markov chain $\mathbf{X} = \{X_j\}$ **with Sensing**:



  - With sensing, the sensing states need to be distinguished from the transmission states.
  - The holding time of each state depends on sensing, backoff scheme, and protocol overhead.
  - $p_{i,t}$: probability of success given that the HOL packet of Node i is transmitted at t.

Characterization of Steady-State Probabilities of Success of HOL Packets $\mathbf{p}$

- Two basic assumptions:
  - **State-independence Assumption**: $\lim_{t\to\infty} p_{i,t} = p_i$, $i \in \mathcal{N}$.
  - **Queue-independence Assumption**: $\beta_{ij} = 1$ for all $i \neq j$, $i, j \in \mathcal{N}$, where

    $$\beta_{ij} = \frac{\Pr\{\text{Node } j\text{'s queue is empty} \mid \text{Node } i\text{'s queue is busy}\}}{\Pr\{\text{Node } j\text{'s queue is empty}\}}$$

    indicates the dependency between queues of Node i and Node j.

- Based on the **state-independence assumption**, the steady-state probability of successful transmission of HOL packets of Node $i \in \mathcal{N}$, p_i, can be written as

$$p_i = \sum_{\mathcal{S}_i \subseteq \mathcal{N}\setminus\{i\}} \Pr\{\text{Success of Node } i \mid \text{Node } i \text{ requests and the set of transmitters with concurrent transmissions is } \mathcal{S}_i\} \cdot \Pr\{\text{Set of transmitters with concurrent transmissions is } \mathcal{S}_i \mid \text{Node } i \text{ requests}\}.$$

Characterization of Steady-State Probabilities of Success of HOL Packets $\mathbf{p}$

- Based on the **queue-independence assumption**, (1) can be written as

$$p_i = \sum_{\mathcal{S}_i \subseteq \mathcal{N} \setminus \{i\}} r_{i|\mathcal{S}_i} \cdot \prod_{j \in \mathcal{S}_i} \omega_j \cdot \prod_{j \in \mathcal{N} \setminus (\mathcal{S}_i \bigcup \{i\})} (1 - \omega_j), \quad i \in \mathcal{N} \qquad (2)$$

  - I_i: Boolean indicator to indicate whether Node i transmits
  - ω_i: Transmission probability of Node i
    - ω_i depends on whether Node i's queue is **unsaturated/saturated** and whether sensing is available.
  - $r_{i|\mathcal{S}_i}$: Conditional success probability of Node i for given set $\mathcal{S}_i$ of transmitters with concurrent transmissions
    - $r_{i|\mathcal{S}_i}$ depends on specific **receiver and channel models**.

A Unified Analytical Framework of Random Access

- Markov renewal process of HOL packets:
  - Various design features of random access (e.g., sensing-based or sensing-free, connection-based or connection-free, backoff, retry limit, ...) can be incorporated.
- Fixed-point equations of steady-state probabilities of successful transmission of HOL packets $\mathbf{p}$:
  - Various receiver and channel models (e.g., collision receiver, capture receiver, SIC receiver, AWGN, Rayleigh fading, ...) can be incorporated.
- Markov renewal process of HOL packets + Fixed-point equations of steady-state probabilities of successful transmission of HOL packets $\mathbf{p}$:
  - Service process of each node's queue can be characterized, based on which various performance metrics can be analyzed and optimized.

Based on the Proposed Unified Analytical Framework

- **Fundamental Limits**
  - Maximum network throughput
  - Minimum mean access/queueing delay
  - Maximum network sum rate
  - Stability region of input rates
- **Insights to Network Design**
  - Optimal tuning of backoff parameters (transmission probability, backoff window size, ...) based on the long-term traffic input rates of nodes
  - Effects of key factors (sensing, backoff function, connection establishment, network size, receiver design, ...) on limiting performance and performance tradeoffs
  - Applications to practical networks

A Glimpse of Our Work

<table>
<tr><th rowspan="2"></th><th rowspan="2">Aloha</th><th rowspan="2">CSMA</th><th rowspan="2">WiFi Networks</th><th colspan="2">4G/5G Networks</th></tr>
<tr><th>Licensed Bands</th><th>Unlicensed Bands</th></tr>
<tr><td rowspan="2">Network Throughput Optimization</td><td>[Dai’12]
[Gao-Dai’19]</td><td>[Dai’13], [Sun-Dai’16]
[Gao-Dai’19]</td><td rowspan="2">[Dai-Sun’13], [Gao-Sun-Dai’13], [Gao-Dai’13], [Gao-Sun-Dai’14], [Sun-Dai’15], [Sun-Dai’16], [Gao-Dai-Hei’17]</td><td rowspan="2">[Zhan-Dai’18]
[Zhan-Dai’19]</td><td rowspan="2">[Sun-Dai’20]</td></tr>
<tr><td colspan="2">[Gao-Fang-Song-Dai’23]</td></tr>
<tr><td rowspan="2">Delay Optimization</td><td>[Dai’12]
[Li-Zhan-Dai’21]
[Zhao-Dai’24]
[Wang-Dai-Sun’24]</td><td>[Dai’13], [Sun-Dai’16]</td><td rowspan="2">[Dai-Sun’13], [Sun-Dai’15], [Sun-Dai’16]</td><td rowspan="2">[Zhan-Dai’19]
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<tr><td>Network Sum Rate Optimization</td><td>[Li-Dai’16]
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<tr><td>Stability Region</td><td>[Dai’22]
[Yang-Dai’23]</td><td>[Dai’25]</td><td></td><td></td><td></td></tr>
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Learning-Based Random Access

More "Intelligent" Access Design: From a Learning Perspective

- From a learning perspective, finding the **optimal access strategy** for each node can be formulated as a **sequential decision-making** problem:

  Each node **independently decides** when to access based on its own **observations/measurements and past experience**.

- To solve sequential decision-making problems, **reinforcement learning (RL)** has been widely adopted.

Learning-Based Random Access

- The majority of the existing learning-based random access schemes focused on the throughput performance.

- **Abundant improvement in network throughput demonstrated**:

  Without sensing, the network throughput with the simple collision receiver can far exceed the well-known limit of e^{-1}.

  - **Q-learning-based Framed Slotted Aloha** [Chu&etc'2015]
  - **Deep Q-Network (DQN)-based Multichannel Slotted Aloha** [Naparstek&Cohen'2019], [Zhong&etc'2019], [Sohaib,Jeong&Jeon'2022], [Jadoon&etc'2024], [Han&etc'2024],...
  - **Multi-Armed-Bandit (MAB) based Aloha [Peng&Dai'2024]**: Achieve the maximum network throughput of 1

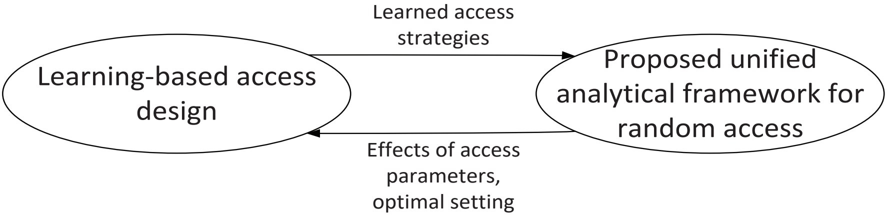
Learning-Based Random Access

- Most are direct applications of existing RL algorithms.
- Design based on intuition and experience: More like an art than a science?
- Due to the lack of analytical framework, effects of key learning parameters such as the learning rate cannot be fully understood.

- *How can the proposed theory of random access guide the design of learning-based random access?*

Queueing-Theoretical Framework for Learning-Based Access Design

- **Proposed unified analytical framework for learning-based access design**: Helpful for understanding **why** they perform well, and how to further **optimize** the performance
  - Identify the learned access strategies.
  - Feed the learned access strategies into the analytical framework of random access for performance optimization.



Example: Throughput-Optimal Random Access

- With the collision receiver, the maximum network throughput of n-node slotted Aloha is $\left(\frac{n-1}{n}\right)^{n-1} \approx e^{-1}$ for large n.
- MAB-based Aloha [Peng&Dai'2024]
  - The maximum network throughput of 1 is achieved.
    Why/when is the throughput limit e^{-1} broken?
  - Serious unfairness among nodes is observed with MAB-based Aloha.
    What is the optimal throughput-fairness tradeoff?
  - Both throughput and fairness depend on the learning rate.
    How to choose the learning rate to achieve the optimal throughput-fairness tradeoff?

N. Peng and L. Dai, "Multi-Armed-Bandit-based Framed Slotted Aloha for Throughput Optimization," *IEEE Commun. Lett.*, vol. 28, no. 42, pp. 847-851, Apr. 2024.

Example: Throughput-Optimal Random Access

How can the proposed theory of random access guide the design of learning-based random access?

- Identify the learned access strategies:
  - **New** access strategies learned by MAB-based Aloha.
- Feed the learned access strategies into the analytical framework of random access for performance optimization:
  - With the new access strategies, the assumption of state-independent probability of successful transmission of HOL packets, which has been adopted in all previous analytical models, no longer holds.
  - The proposed unified analytical framework of random access needs to be extended to incorporate a **state-dependent** probability of successful transmission of HOL packets [Dai'2025].

L. Dai, "Harnessing the Channel-Capture Phenomenon in Slotted Aloha for Achieving the Optimal Tradeoff between Throughput and Short-Term Fairness," *IEEE Trans. Commun.*, vol. 73, no. 9, pp. 8301–8313, Sept. 2025.

MAB-Based Aloha

- Node throughput: $\lambda_{out,i} = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} N_{i,t}$
  $N_{i,t}$: the number of successfully transmitted packets of Node i in time slot t.
- Reward: $r_t^i = N_{i,t}$
  For each node, maximizing the cumulative reward is equivalent to maximizing its throughput.
- Action: $A_t^i \in \{1, \cdots, L+1\}$, L is the number of null actions.
  $A_t^i = 1$ indicates that Node i transmits at time slot t.
- $A_t^i = \arg\max_{a\in\{1,\cdots,L+1\}} Q(i,a)$, where $Q(i,a)$ denotes the mean reward of action a estimated by Node i, i.e., the Q value, which is updated as $Q(i,A_t^i) \leftarrow Q(i,A_t^i) + \alpha(r_t^i - Q(i,A_t^i))$.

MAB-Based Aloha

- The network throughput $\hat{\lambda}_{out}$ depends on the learning rate α and the number of null actions L:

$$\lim_{L\to\infty} \hat{\lambda}_{out} = \begin{cases} \frac{n}{2n-1} & \alpha = 1 \\ 1 & \alpha < 1. \end{cases}$$

- When $\alpha < 1$, only one node has non-zero throughput. The other $n-1$ nodes can never transmit successfully, indicating serious unfairness.
- To improve fairness, introduce a threshold Q_{th}, below which the Q value is reset to zero.
  - After a few unsuccessful transmissions, the node that once occupies the channel would have zero Q value and start to contend with others again.
  - Both the network throughput and fairness performance depend on the threshold Q_{th} and learning rate α.
- *How to optimize the throughput-fairness tradeoff?*

MAB-Based Aloha

- The learned access strategy for each node: Transmit with probability 1 if the Q value is no smaller than Q_{th}. Otherwise transmit with probability $\frac{1}{L+1}$.
- When $L \gg 1$: A node may capture the channel and transmit exclusively for a long period.
- With the above channel-capture phenomenon, the probability of successful transmissions of HOL packets becomes state dependent: A fresh HOL packet would see much lower contention than those in deep backoff, and thus enjoy a much higher probability of success.

Unified Analytical Framework of Random Access: State-Dependent Probability of Success

- The states of HOL packets are divided into two categories: capture and non-capture.
- Define a state as a *Capture State* if it satisfies the following two conditions:
  - If a HOL packet is in a capture state, then the probability of successful transmission of other HOL packets is zero;
  - If a HOL packet is in a capture state, then no other HOL packets can be in a capture state.
- Let $p_{i,t}^{(k)}$ denote the probability of successful transmission of Node $i \in \mathcal{N}$ if its HOL packet is in the k-th backoff stage, $k = 0, \ldots, K$. $p_i^{(k)} = \lim_{t\to\infty} p_{i,t}^{(k)}$.

Unified Analytical Framework of Random Access: State-Dependent Probability of Success

- Symmetric case:

$$p^{(k)} = \begin{cases} p_C & k = 0, \dots, n_C - 1 \\ p_{\bar{C}} & k = n_C, \dots, K, \end{cases}$$

where

$$p_C = (1-\tilde{q})^{n-1}, \quad p_{\bar{C}} = \frac{p_C}{1 + \frac{(n-1)p_C\tilde{q}}{(1-p_C)^{n_C}}\left(1 + \sum_{l=1}^{n_C-1}\frac{(1-p_C)^l}{\mathcal{Q}_l}\right)}.$$

$\tilde{q}$ is the average transmission probability of non-capture states. n_C is the number of capture states.

- As $\tilde{q} \to 0$,

$$p_C \to 1, \quad p_{\bar{C}} \to \begin{cases} \frac{1}{2} & n_C = 1 \\ 0 & n_C \geq 2. \end{cases}$$

Unified Analytical Framework of Random Access: Network Throughput and Short-term Fairness Index

- Network throughput: $\hat{\lambda}_{out} = \sum_{i=1}^{n} \lim_{t\to\infty} \lambda_{out,i}^{t}$;

  Short-term fairness index: $J_t = \frac{\left(\sum_{i=1}^{n} \lambda_{out,i}^{t}\right)^2}{n\sum_{i=1}^{n}(\lambda_{out,i}^{t})^2}$;

  where $\lambda_{out,i}^{t}$ denotes the output rate of Node i's queue by time t.

- Both network throughput $\hat{\lambda}_{out}$ and short-term fairness index J_t depend on the probability of success in capture states p_C and the probability of success in non-capture states $p_{\bar{C}}$.

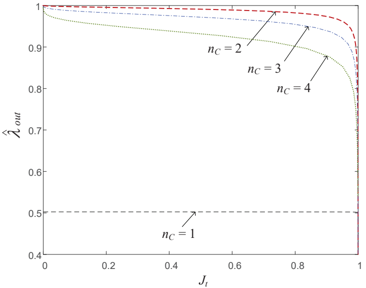
Unified Analytical Framework of Random Access: Optimal Throughput-Fairness Tradeoff

- For given number of capture states $n_C > 0$: the tradeoff between network throughput and short-term fairness is determined by the average transmission probability of non-capture states $\tilde{q}$:

  The smaller $\tilde{q}$, the higher network throughput, the worse short-term fairness.

- The optimal tradeoff between network throughput and short-term fairness is achieved when $n_C = 2$:

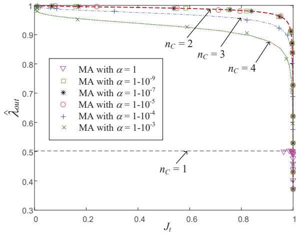
$$J_t \approx \frac{1}{1+\frac{8n}{\left(\frac{1}{\hat{\lambda}_{out}}-1\right)^2}\cdot\frac{1}{t}}.$$



MAB-Based Aloha: To Achieve the Optimal Throughput-Fairness Tradeoff

- The learned access strategy for each node: Transmit with probability 1 if the Q value is no smaller than Q_{th}. Otherwise transmit with probability $\frac{1}{L+1}$.
  - The number of capture states n_C is determined by the learning rate α and the Q-value threshold Q_{th}: $n_C = \lceil \log_{1-\alpha} Q_{th} \rceil$.
  - The non-capture transmission probability $\tilde{q}$ is determined by the number of null actions L: $\tilde{q} = \frac{1}{L+1}$.

- To achieve the optimal throughput-fairness tradeoff, the learning rate α and the Q-value threshold Q_{th} of the proposed MAB-based Aloha should satisfy: $\lceil \log_{1-\alpha} Q_{th} \rceil = 2$



$L \in \{10^2, \ldots, 10^6\}$. $n = 100$. $t = 10^7$ slots. $Q_{th} = 10^{-10}$.

In the Future...

To support *more devices* with *higher QoS requirements* with *better robustness*:

- Lower latency: What is the delay-optimal access strategy?
- Longer lifetime: How to jointly optimize transmission power/rate with access strategy? When to sleep?
- More BSs/APs: How should BSs/APs coordinate with each other?
- More resilient: How to cope with highly dynamic environments?

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Thank You!

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