Random Access: Packet-Based or Connection-Based?

Lin Dai

Department of Electrical Engineering
City University of Hong Kong

lindai@cityu.edu.hk

March 2021

Outline

- Random Access for Machine-to-Machine (M2M) Communications
- A Unified Theory of Random Access
- Packet-Based or Connection-Based: Comparison of Maximum Effective Throughput

Random Access for Machine-to-Machine (M2M) Communications

M2M Communications

- M2M communications is expected to play a dominant role in the next-generation communication networks.
  - 80 billions machine-type devices to be connected to mobile networks by 2025
  - Wide applications 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: mMTC (massive Machine-Type Communications) and URLLC (Ultra-Reliable Low-Latency Communications)

Features of M2M Communications

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

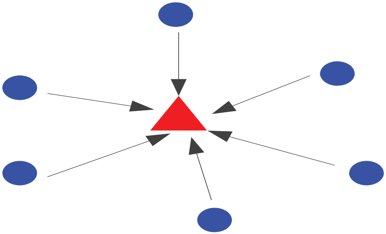
- M2M Communications:

  — massive number of devices

  — short packet payload

- How to provide pervasive and efficient access for M2M communications?

Multiple Access (MAC)

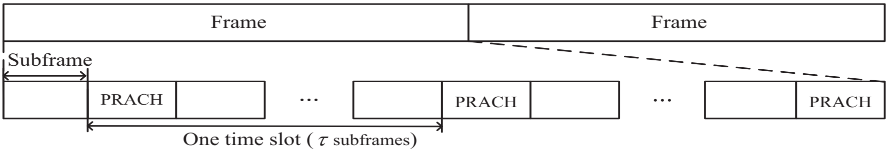


Multiple users transmit to a common receiver: How to share the resources?

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

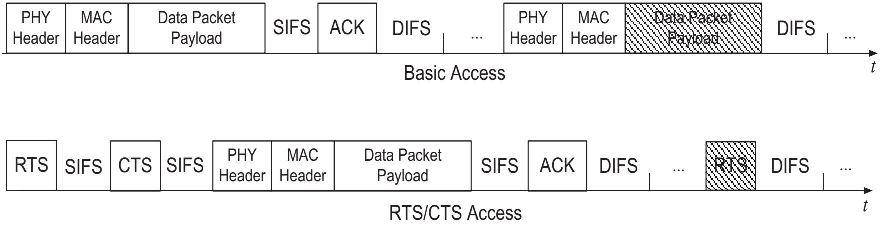
MAC in Cellular Networks

- Step 1: Random access – Each user independently sends requests to the base station (BS) to initiate a connection.
- Step 2: Centralized access – Upon successfully receiving a request, the BS allocates resources to the successful user for data transmission.

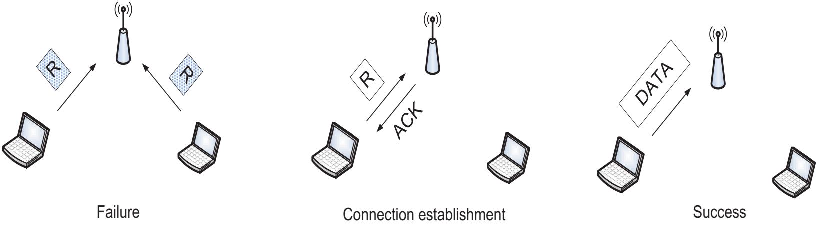


MAC in WiFi Networks

- Basic access: Random access for data transmission
- Request-to-Send/Clear-to-Send (RTS/CTS) access: Random access for requests + Fixed-length data transmission

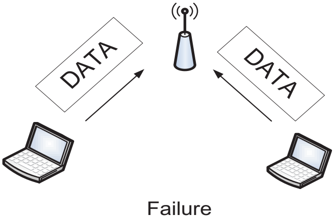


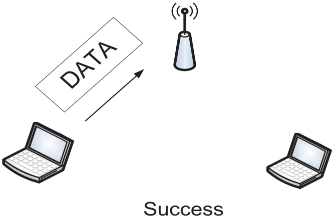
Connection-Based Random Access



- With connection-based random access, each user sends a **short request** to the receiver first, and transmits its data packets only after the receiver acknowledges that the request is successfully received, i.e., a connection is established.
- **The data packets do not contend**. The receiver may either allocate resources dynamically based on the request (e.g., cellular networks), or reserve a fixed amount of resources (e.g., RTS/CTS access of WiFi networks).

Packet-Based (Connection-Free) Random Access





- With packet-based random access, **every data packet needs to contend** for channel access (e.g., basic access of WiFi networks).
- Less overhead compared to connection-based random access
- The time wasted in each transmission failure is determined by the length of a data packet.

M2M Communications: Connection-Based or Connection-Free?

M2M Communications: Connection-Based or Connection-Free?

- Intuitively, there exists a critical threshold of the data packet transmission time, only above which establishing a connection is beneficial.

M2M Communications: Connection-Based or Connection-Free?

- Intuitively, there exists a critical threshold of the data packet transmission time, only above which establishing a connection is beneficial.

Questions to Answer:

- WiFi networks: When to activate the connection-based RTS/CTS access?
- 5G networks: Should the current connection-based (grant-based) access be replaced by a grant-free one?
- Future networks: Connection-based or connection-free?

A Unified Theory of Random Access

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]

  - What if nodes cannot sense the channel correctly?
  - Send a short request and be notified by the receiver about the availability of the channel.

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.

Question 3: What if the Transmission Fails?

- 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): $\mathcal{Q}(i) = 2^{-i}$.
    Uniform Backoff: $\mathcal{Q}(i) = 1$.

Design Freedoms of Random-Access Networks

- Sensing-free (Aloha) or Sensing-based (CSMA)
- Packet-based or Connection-based
- Backoff: Constant, Exponential, ...
- Receiver: Collision, Capture, SIC, ...
- ...

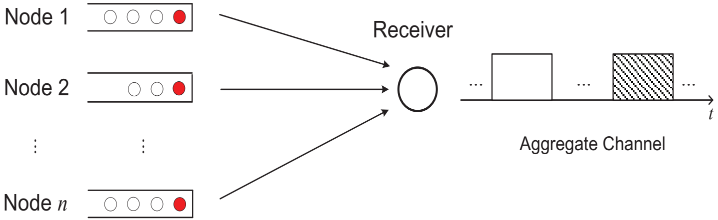
Performance Metrics of Random-Access Networks

- 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.
- ...

Modeling of Random-Access Networks

- Numerous models have been developed for various random-access schemes to tackle different problems.
- Inconsistent or even contradictory results were obtained due to differences in modeling assumptions and approaches.
- The existing models can be roughly divided into two categories: **channel-centric** or **node-centric**.

Modeling of Random-Access Networks: Channel-Centric

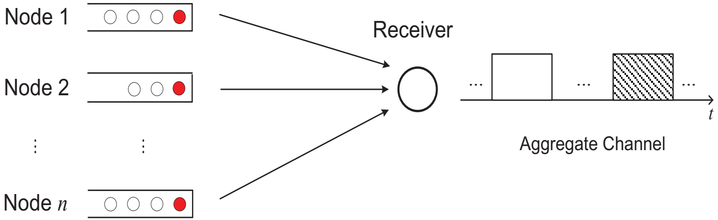


- Channel-centric modeling: to characterize the aggregate traffic of *all* the nodes.

  — Capture the essence of contention among nodes and simplify the throughput analysis.

  — Difficult to analyze the queueing performance of each node.

Modeling of Random-Access Networks: Node-Centric



- Node-centric modeling: to characterize the queueing behavior of each node.

  — High modeling complexity when interactions among nodes' queues are taken into consideration.

  — Models were customized for specific networks.

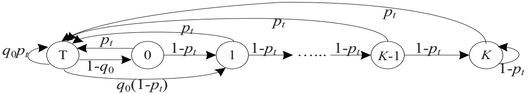
Toward a Unified and Scalable Analytical Framework

- Unified Analytical Framework
  - Incorporate all design freedoms and performance metrics
  - Analysis of different random-access schemes can all be based on the same framework.
- Scalable Analytical Framework
  - Modeling complexity does not increase with the network size.

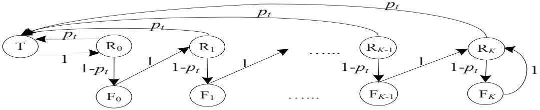
Modeling of HOL Packets

Each HOL packet can be modeled as a discrete-time Markov renewal process $(\mathbf{X}^h, \mathbf{V}^h) = \{(X_j^h, V_j^h), j = 0, 1, \ldots\}$.

The embedded Markov chain $\mathbf{X}^h = \{X_j^h\}$ **Without Sensing**:



The embedded Markov chain $\mathbf{X}^h = \{X_j^h\}$ **With Sensing**:



- With sensing, the sensing states need to be distinguished from the transmission states.
- The holding time of each state depends on sensing and backoff.
- p_t: probability of success given that the HOL packet is transmitted at t. $\lim_{t\to\infty} p_t = p$.

Key to Establishing a Unified and Scalable Analytical Framework

- For performance analysis of a **multi-queue-single-server** system, the main challenge lies in the characterization of the **service process**.
- Key ingredients for a unified and scalable analytical framework of random access [Dai'12] [Dai'13]:
  - Modeling of each HOL packet's behavior: Discrete-time Markov renewal process
  - Characterization of steady-state probability of being successfully decoded (served) of each HOL packet $\boldsymbol{p}$: Fixed-point equations of $\boldsymbol{p}$

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

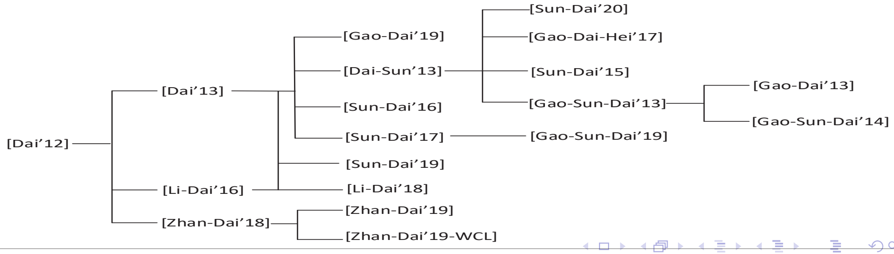
L. Dai, "Toward a coherent theory of CSMA and Aloha," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3428–3444, Jul. 2013.

Based on Our Proposed Analytical Framework

- **Fundamental Limits**
    - Maximum network throughput
    - Minimum mean access/queueing delay
    - Maximum network sum rate
- **Insights to Network Design**
    - Optimal tuning of backoff parameters (transmission probability, backoff window size, ...)
    - Effects of key factors (sensing, backoff function, network size, receiver design, ...) on limiting performance and performance tradeoffs
    - Applications to practical networks

A Glimpse of Our Work

	Aloha	CSMA	WiFi Networks	LTE Networks	
				Licensed Bands	Unlicensed Bands
Network Throughput Optimization	[Dai'12] [Gao-Dai'19]	[Dai'13], [Sun-Dai'16] [Gao-Dai'19]	[Dai-Sun'13], [Gao-Sun-Dai'13], [Gao-Dai'13], [Gao-Sun-Dai'14], [Sun-Dai'15], [Sun-Dai'16], [Gao-Dai-Hei'17]	[Zhan-Dai'18] [Zhan-Dai'19]	[Sun-Dai'20]
Delay Optimization	[Dai'12]	[Dai'13], [Sun-Dai'16]	[Dai-Sun'13], [Sun-Dai'15], [Sun-Dai'16]	[Zhan-Dai'19-WCL]	
Network Sum Rate Optimization	[Li-Dai'16] [Li-Dai'18]	[Sun-Dai'17] [Sun-Dai'19]	[Sun-Dai'17], [Gao-Sun-Dai'19]		



References

- L. Dai, "Stability and delay analysis of buffered Aloha networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 2707–2719, Aug. 2012.
- 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 and X. Sun, "A unified analysis of IEEE 802.11 DCF networks: stability, throughput and delay," *IEEE Trans. Mobile Computing*, vol. 12, no. 8, pp. 1558–1572, Aug. 2013.
- Y. Gao, X. Sun, and L. Dai, "Throughput Optimization of Heterogeneous IEEE 802.11 DCF Networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 1, pp. 398–411, Jan. 2013.
- Y. Gao and L. Dai, "Optimal Downlink/Uplink Throughput Allocation for IEEE 802.11 DCF Networks," *IEEE Wireless Commun. Letters*, vol. 2, no. 6, pp. 627–630, Dec. 2013.
- Y. Gao, X. Sun, and L. Dai, "IEEE 802.11e EDCA Networks: Modeling, Differentiation and Optimization," *IEEE Trans. Wireless Commun.*, vol. 13, no. 7, pp. 3863–3879, July 2014.

References

- X. Sun and L. Dai, "Backoff Design for IEEE 802.11 DCF Networks: Fundamental Tradeoff and Design Criterion," *IEEE/ACM Trans. Networking*, vol. 23, no. 1, pp. 300–316, Feb. 2015.
- Y. Li and L. Dai, "Maximum Sum Rate of Slotted Aloha with Capture," *IEEE Trans. Commun.*, vol. 64, no. 2, pp. 690–705, Feb. 2016.
- X. Sun and L. Dai, "Performance Optimization of CSMA Networks with A Finite Retry Limit," *IEEE Trans. Wireless Commun.*, vol. 15, no. 9, pp. 5947–5962, Sept. 2016.
- X. Sun and L. Dai, "Fairness-constrained Maximum Sum Rate of Multi-rate CSMA Networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1741–1754, Mar. 2017.
- Y. Gao, L. Dai and X. Hei, "Throughput Optimization of Multi-BSS IEEE 802.11 Networks With Universal Frequency Reuse," *IEEE Trans. Commun.*, vol. 65, no. 8, pp. 3399–3414, Aug. 2017.
- W. Zhan and L. Dai, "Massive Random Access of Machine-to-Machine Communications in LTE Networks: Modeling and Throughput Optimization," *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2771-2785, Apr. 2018.

References

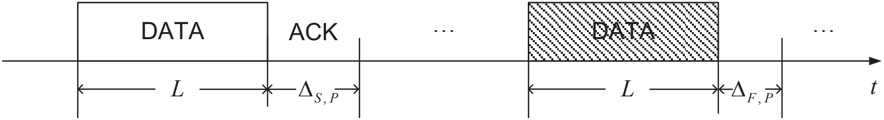
- Y. Li and L. Dai, "Maximum Sum Rate of Slotted Aloha with Successive Interference Cancellation," *IEEE Trans. Commun.*, vol. 66, no. 11, pp. 5385-5400, Nov. 2018.
- Y. Gao, X. Sun, and L. Dai, "Sum Rate Optimization of Multi-Standard IEEE 802.11 WLANs," *IEEE Trans. Commun.*, vol. 64, no. 7, pp. 3055-3068, Apr. 2019.
- Y. Gao and L. Dai, "Random Access: Packet-Based or Connection-Based?" *IEEE Trans. Wireless Commun.*, vol. 18, no. 5, pp. 2664-2678, May 2019.
- X. Sun and L. Dai, "To Sense or Not To Sense: A Comparative Study of CSMA with Aloha," *IEEE Trans. Commun.*, vol. 67, no. 11, pp. 7587-7603, Nov. 2019.
- W. Zhan and L. Dai, "Massive Random Access of Machine-to-Machine Communications in LTE Networks: Throughput Optimization with a Finite Data Transmission Rate," *IEEE Trans. Wireless Commun.*, vol. 18, no. 12, pp. 5749-5763, Dec. 2019.
- X. Sun and L. Dai, "Towards Fair and Efficient Spectrum Sharing between LTE and WiFi in Unlicensed Bands: Fairness-constrained Throughput Maximization," *IEEE Trans. Wireless Commun.*, vol. 19, no. 4, pp. 2713-2727, Apr. 2020.

Packet-Based or Connection-Based:
Comparison of Maximum Effective Throughput

Y. Gao and L. Dai, "Random Access: Packet-Based or Connection-Based?" *IEEE Trans. Wireless Commun.* vol. 18, no. 5, pp. 2664–2678, May 2019.

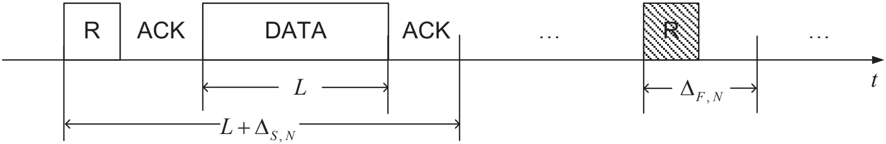
Packet-Based Random Access

- Every data packet has to contend for channel access.
- The transmission failure time is determined by the length of a data packet.



Connection-Based Random Access

- Each node sends a short request to the receiver first, and transmits its data packet only after the receiver acknowledges that the request is successfully received, i.e., a connection is established.
- The transmission failure time is determined by the length of a request, which is usually much smaller than that of a data packet.



Maximum Network Throughput

- Network Throughput: the average number of successfully decoded packets of the network per time slot.
  - With the collision model, at most one packet can be successfully decoded in each time slot. The network throughput is also the fraction of time that the network has a successful packet transmission.

- The maximum network throughput $\hat{\lambda}_{\max} = \max_{\hat{\lambda},\{q_i\}} \hat{\lambda}_{out}$ is closely dependent on whether nodes sense the channel or not.
  - **Without sensing (Aloha)**: $\hat{\lambda}^A_{\max} = \frac{\tau_S}{\tau_S - 1 + e}$.
  - **With sensing (CSMA)**: $\hat{\lambda}^C_{\max} = \frac{\tau_S - 1}{\tau_S - \tau_C - (\tau_C - 1)\mathbb{W}_0^{-1}\left(-\frac{\tau_C - 1}{\tau_C} \cdot e^{-1}\right)}$.

τ_S: successful transmission time; τ_C: failed transmission time

- Both τ_S and τ_C crucially depend on whether the network is packet-based or connection-based.

Maximum Effective Throughput

- To compare the throughput performance of packet-based and connection-based random access, we need to take the overhead into account.
- Let L, Δ_S and Δ_F denote the transmission time of a data packet, the overhead time for each successful or failed transmission, respectively, all in the unit of seconds.
- Define the effective throughput η_{out} as the fraction of time that is spent on the data payload transmission: $\eta_{out} = \frac{L}{L+\Delta_S} \cdot \hat{\lambda}_{out}$.
- The maximum effective throughput is given by

$$\eta_{\max} = \frac{L}{L + \Delta_S} \cdot \hat{\lambda}_{\max}.$$

Maximum Effective Throughput: Packet-Based Random Access

Packet-Based Aloha

- $\tau_S = \tau_C = 1$ time slot.
- The maximum effective throughput of packet-based Aloha is given by

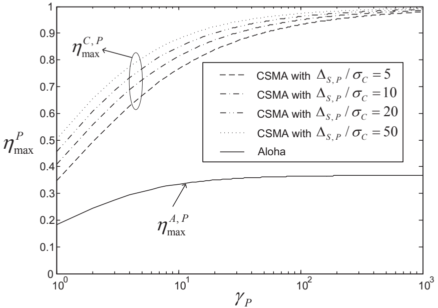
$$\eta_{\max}^{A,\,P} = \frac{L}{L + \Delta_{S,\,P}} \cdot e^{-1}.$$

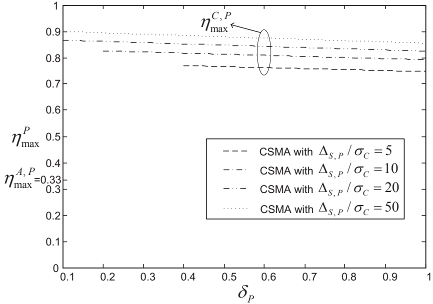
Packet-Based CSMA

- The length of each time slot σ_C is determined by the sensing time.
- $\tau_S = \frac{L+\Delta_{S,\,P}}{\sigma_C} + 1$ time slot, $\tau_C = \frac{L+\Delta_{F,\,P}}{\sigma_C} + 1$ time slot.
- The maximum effective throughput of packet-based CSMA is given by

$$\eta_{\max}^{C,\,P} = \frac{-L \cdot \mathbb{W}_0\left(-\frac{L+\Delta_{F,\,P}}{e(L+\Delta_{F,\,P}+\sigma_C)}\right)}{L+\Delta_{F,\,P} - \left(\Delta_{S,\,P} - \Delta_{F,\,P}\right)\mathbb{W}_0\left(\frac{-L-\Delta_{F,\,P}}{e(L+\Delta_{F,\,P}+\sigma_C)}\right)}.$$

Maximum Effective Throughput: Packet-Based Random Access





- Let $\gamma_P = \frac{L}{\Delta_{S,\ P}}$ and $\delta_P = \frac{\Delta_{F,\ P}}{\Delta_{S,\ P}}$. As $\gamma_P \to \infty$, $\eta_{\max}^{A,\ P} \to e^{-1}$ and $\eta_{\max}^{C,\ P} \to 1$.
  - The access efficiency can always be improved by increasing the data packet transmission time L. Yet the gain could become marginal when sensing is not available.
  - The collision time is mainly determined by the data packet transmission time L. Reducing the overhead time $\Delta_{F,\ P}$ only brings negligible gain.

Maximum Effective Throughput: Connection-Based Random Access

Connection-Based Aloha

- $\tau_S = \frac{L+\Delta_{S,\,N}}{\Delta_{F,\,N}}$ time slot, $\tau_C = 1$ time slot
- The maximum effective throughput of connection-based Aloha is given by

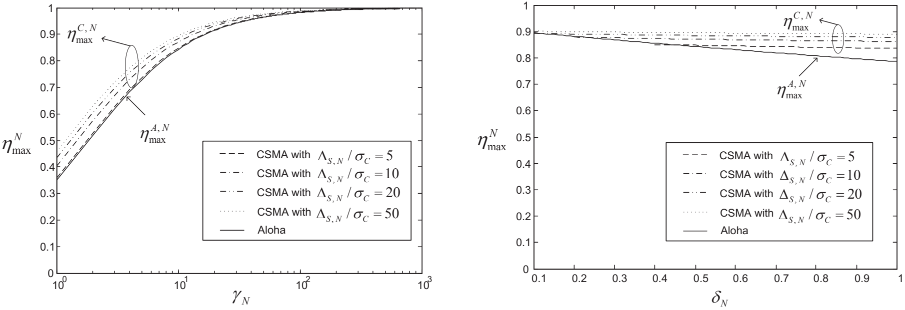
$$\eta_{\max}^{A,\,N} = \frac{L}{L + \Delta_{S,\,N} + (e-1)\Delta_{F,\,N}}.$$

Connection-Based CSMA

- $\tau_S = \frac{L+\Delta_{S,\,N}}{\sigma_C} + 1$ time slot, $\tau_C = \frac{\Delta_{F,\,N}}{\sigma_C} + 1$ time slot.
- The maximum effective throughput of connection-based CSMA is given by

$$\eta_{\max}^{C,\,N} = \frac{-L \cdot \mathbb{W}_0\left(-\frac{\Delta_{F,\,N}}{e(\Delta_{F,\,N}+\sigma_C)}\right)}{\Delta_{F,\,N} - (L + \Delta_{S,\,N} - \Delta_{F,\,N})\,\mathbb{W}_0\left(-\frac{\Delta_{F,\,N}}{e(\Delta_{F,\,N}+\sigma_C)}\right)}.$$

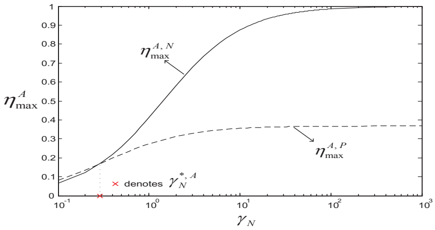
Maximum Effective Throughput: Connection-Based Random Access

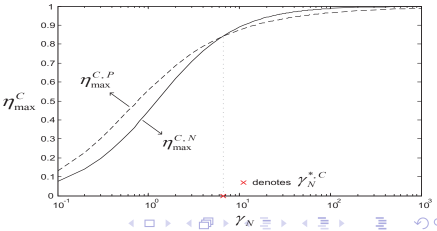


- Let $\gamma_N = \frac{L}{\Delta_{S,\ N}}$ and $\delta_N = \frac{\Delta_{F,\ N}}{\Delta_{S,\ N}}$. As $\gamma_N \to \infty$, $\eta_{\max}^{A,\ N} \to 1$ and $\eta_{\max}^{C,\ N} \to 1$.
  - The improvement in throughput achieved by CSMA over Aloha becomes marginal especially when the data packet transmission time L is large or the overhead time for each failed transmission $\Delta_{F,\ N}$ is small.

Comparison of Packet-Based and Connection-Based Random Access

- Whether the overhead of establishing a connection overweighs its benefit depends on the data packet transmission time L.
  - Cost of connection establishment: $\Delta_{S,\,N} > \Delta_{S,\,P}$;
  - Benefit of connection establishment: $\Delta_{F,\,N} < L + \Delta_{F,\,P}$.
- For both Aloha and CSMA networks, the connection-based maximum effective throughput exceeds the packet-based maximum effective throughput only when $\gamma_N = \frac{L}{\Delta_{S,\,N}}$ is sufficiently large.





Connection-Establishment Threshold

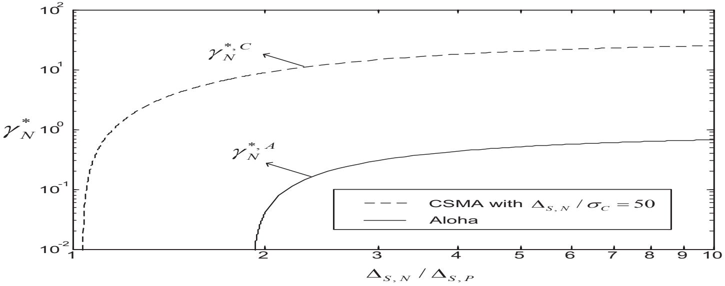
- To find out when connection-based random access outperforms packet-based random access, define γ_N^* as the threshold for beneficial connection establishment, i.e., $\eta_{\max}^N \geq \eta_{\max}^P$ if $\gamma_N \geq \gamma_N^*$.
  - Aloha: $\gamma_N^{*,\,A} = \frac{1 - e \cdot \frac{\Delta_{S,\,P}}{\Delta_{S,\,N}}}{e-1} + \delta_N$.
  - CSMA:

$$\gamma_N^{*,\,C} = \frac{-\frac{\sigma C}{\Delta_{S,\,N}} - (b - \frac{\sigma C}{\Delta_{S,\,N}})\mathbb{W}_0\left(-\frac{b}{b-\frac{\sigma C}{\Delta_{S,\,N}}}\exp\left\{-\frac{b}{b-\frac{\sigma C}{\Delta_{S,\,N}}}\right\}\right)}{1+(1-\frac{\sigma C}{\Delta_{S,\,N}\cdot b})\mathbb{W}_0\left(-\frac{b}{b-\frac{\sigma C}{\Delta_{S,\,N}}}\exp\left\{-\frac{b}{b-\frac{\sigma C}{\Delta_{S,\,N}}}\right\}\right)} - \delta_P \cdot \frac{\Delta_{S,\,P}}{\Delta_{S,\,N}},$$

where $b = -\frac{\delta_N}{\mathbb{W}_0\left(-\frac{\delta_N}{e(\delta_N + \frac{\sigma C}{\Delta_{S,\,N}})}\right)} + 1 - \frac{\Delta_{S,\,P}}{\Delta_{S,\,N}} - \delta_N$.

$\delta_P = \frac{\Delta_{F,P}}{\Delta_{S,P}}$ and $\delta_N = \frac{\Delta_{F,N}}{\Delta_{S,N}}$.

Connection-Establishment Threshold



- $\gamma_N^{*,A}$ and $\gamma_N^{*,C}$ both increase with $\frac{\Delta_{S,N}}{\Delta_{S,P}}$.
  - An increase in $\frac{\Delta_{S,N}}{\Delta_{S,P}}$ indicates a higher cost of establishing a connection. Therefore, a larger data packet transmission time is required for connection-based random access to outperform packet-based random access.
- $\gamma_N^{*,A} \ll \gamma_N^{*,C}$.
  - **The benefit from connection establishment is more significant when sensing is absent**.

Implications to M2M Communications

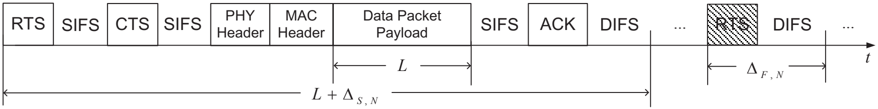
Our Question List:

- WiFi networks: When to activate the connection-based RTS/CTS access?
- 5G networks: Should the current connection-based (grant-based) access be replaced by a grant-free one?
- Future networks: Connection-based or connection-free?

WiFi Networks: Basic Access vs. RTS/CTS Access

- Basic access: packet-based CSMA

- RTS/CTS access: connection-based CSMA



An Illustrative Example

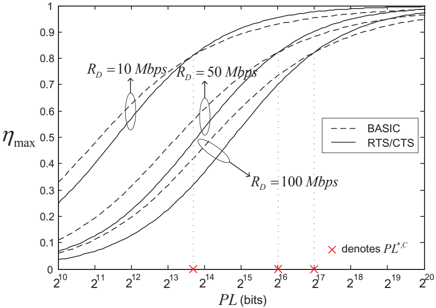
Table: System Parameter Setting in the 802.11ac Standard

PHY Header	20 μs
MAC Header	288 bits
ACK	112 bits+PHY header
RTS	160 bits+PHY header
CTS	112 bits+PHY header
DIFS	34 μs
SIFS	16 μs
Slot Time σ_C	9 μs
Packet Length PL	Up to 2^{23} bits
Data Rate R_D	Up to 96.3 Mbps
Basic Rate R_B	Up to 54 Mbps

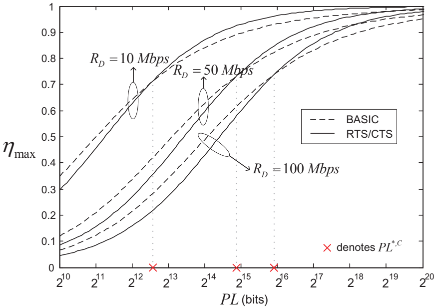
- $\Delta_{S,\,P} = \frac{288}{R_D} + \frac{112}{R_B} + 90$
- $\Delta_{F,\,P} = \frac{288}{R_D} + 54$
- $\Delta_{S,\,N} = \frac{288}{R_D} + \frac{384}{R_B} + 162$
- $\Delta_{F,\,N} = \frac{160}{R_B} + 54$
- $L = \frac{PL}{R_D}$

(all in the unit of μs)

Maximum Effective Throughput



(a) $R_B = 6$ Mbps



(b) $R_B = 54$ Mbps

- RTS/CTS access mechanism outperforms basic access mechanism only when the packet payload length PL is sufficiently large.
- Define $PL^{*,C}$ as the threshold of packet payload length for the RTS/CTS access mechanism to outperform the basic access mechanism, i.e., $\eta_{\max}^{RTS} \geq \eta_{\max}^{BASIC}$ if $PL \geq PL^{*,C}$.
- $PL^{*,C}$ increases as the data rate R_D increases or the basic rate R_B decreases.

Threshold of Packet Payload Length $PL^{*,C}$

- The threshold of packet payload length $PL^{*,C} = g(R_B) \cdot R_D - 288$, where $g(R_B) = \frac{m(9-m)\mathbb{W}_0\left(\frac{m}{9-m}\exp\left\{\frac{m}{9-m}\right\}\right)-9m}{m-(9-m)\mathbb{W}_0\left(\frac{m}{9-m}\exp\left\{\frac{m}{9-m}\right\}\right)} - 54$, with $m = \frac{160+54R_B}{-R_B \cdot \mathbb{W}_0\left(\frac{-160-54R_B}{e(160+63R_B)}\right)} + \frac{112}{R_B} + 18$.

- $PL^{*,C}$ (in the unit of bits) for typical values of data rate R_D and basic rate R_B (in the unit of Mbps):

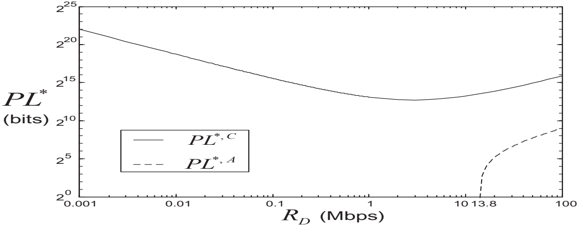
R_B \ R_D	7.2	14.4	21.7	28.9	43.3	57.8	65	72.2	96.3
6	2^{14}	2^{15}	2^{15}	2^{16}	2^{16}	2^{17}	2^{17}	2^{17}	2^{17}
9	2^{13}	2^{14}	2^{15}	2^{15}	2^{16}	2^{16}	2^{17}	2^{17}	2^{17}
12	2^{13}	2^{14}	2^{15}	2^{15}	2^{16}	2^{16}	2^{16}	2^{16}	2^{17}
18	2^{13}	2^{14}	2^{15}	2^{15}	2^{16}	2^{16}	2^{16}	2^{16}	2^{17}
24	2^{13}	2^{14}	2^{14}	2^{15}	2^{15}	2^{16}	2^{16}	2^{16}	2^{17}
36	2^{13}	2^{14}	2^{14}	2^{15}	2^{15}	2^{16}	2^{16}	2^{16}	2^{16}
48	2^{13}	2^{14}	2^{14}	2^{15}	2^{15}	2^{16}	2^{16}	2^{16}	2^{16}
54	2^{13}	2^{14}	2^{14}	2^{15}	2^{15}	2^{16}	2^{16}	2^{16}	2^{16}

Threshold of Packet Payload Length $PL^{*,A}$ without Sensing

- Consider Aloha-based basic access and RTS/CTS access by setting the time slot length to $L + \Delta_{S,P}$ and $\Delta_{F,N}$ in the basic access and RTS/CTS access cases, respectively.
- The threshold of packet payload length without sensing: $PL^{*,A} = \left(\frac{206.3}{R_B} + 5.9\right) \cdot R_D - 288$ bits.
- With $R_B = R_D$, $PL^{*,A} = 5.9 \cdot R_D - 288$ bits, which is non-positive as long as the data rate R_D does not exceed 13.8 Mbps.

What can We Learn from this Example?

- With sensing, the connection-based RTS/CTS access mechanism would be rarely activated as the typical values of packet payload length of MTDs are within hundreds of bytes that could be far below the threshold $PL^{*,C}$.
- When sensing is absent, the connection-based RTS/CTS access usually outperforms the packet-based basic access especially when the data rate is low.



How about 5G Networks?

- A prevailing view:
  - The Aloha-based random access procedure of LTE networks leads to low efficiency due to the connection establishment.
  - For 5G networks, grant-free (packet-based) random access protocols should be adopted, especially for M2M communications with typically small packet payload length.
- There are many factors that lead to low efficiency of LTE random access procedure:
  - Unoptimized backoff parameters (uniform backoff window size and access baring class (ACB) factor)
  - Periodic random access slots
- Without sensing, when properly designed, grant-based random access protocols can provide higher maximum effective throughput than the grant-free ones even for small data packet length.

A Useful Criterion for Designing New Random Access Protocols

- The connection-establishment threshold for Aloha is non-positive if and only if the following inequality holds:

$$\Delta_{S,\,N} + (e-1)\cdot\Delta_{F,\,N} \leq e\cdot\Delta_{S,\,P}. \qquad (1)$$

- Without sensing, a grant-based random access protocol outperforms a grant-free random access protocol in terms of the maximum effective throughput for any packet payload length when their overhead parameters satisfy (1).

On-going and Future Work

- Optimal delay performance
- More advanced receiver and channel models
- Practical constraints such as energy consumption and latency requirements for M2M communications

Acknowledgement

Collaborative work with my PhD students:

- Yayu Gao (Huazhong University of Science and Technology)
- Xinghua Sun (Sun Yat-sen University)
- Yitong Li (Zhengzhou University)
- Wen Zhan (Sun Yat-sen University)

Thank You!

You may find more information here:
`http://www.ee.cityu.edu.hk/~lindai/`

If you have any questions, please do not hesitate to contact me:
lindai@cityu.edu.hk