Optimal Channel Access Schemes for Wireless LAN under Asynchronous Multiple-Packet Reception (MPR)

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Research Background

***p*-Persistent CSMA**	A user begins a packet transmission with a common probability *p* when it has sensed channel idle, and continues sensing when it has sensed channel busy
Multiple-Packet Reception	Multiple-packet reception (MPR) techniques enable successful receptions of time-overlapping packets at the physical layer.

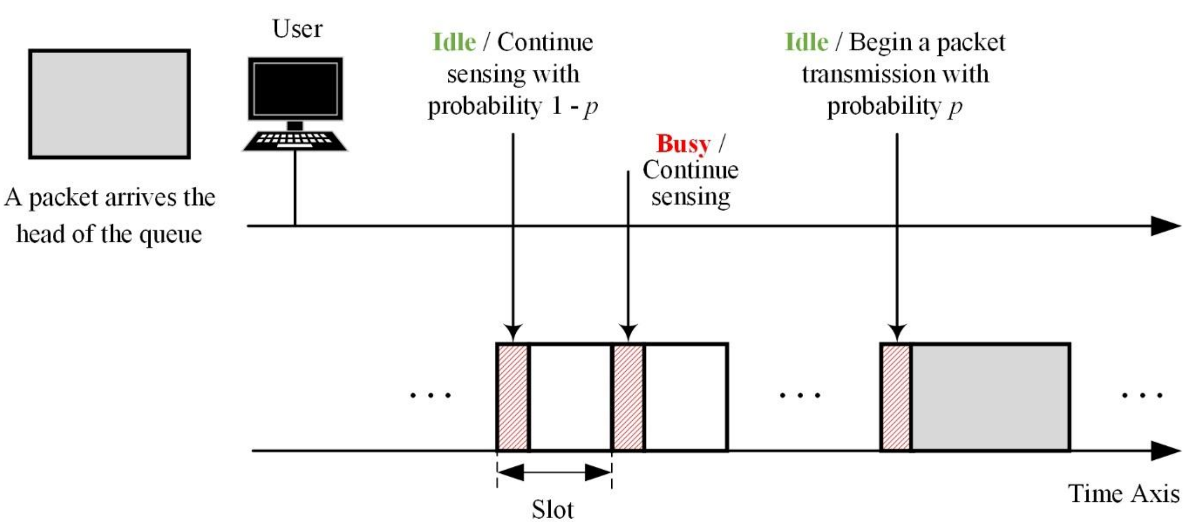


Figure 1. *p*-persistent CSMA

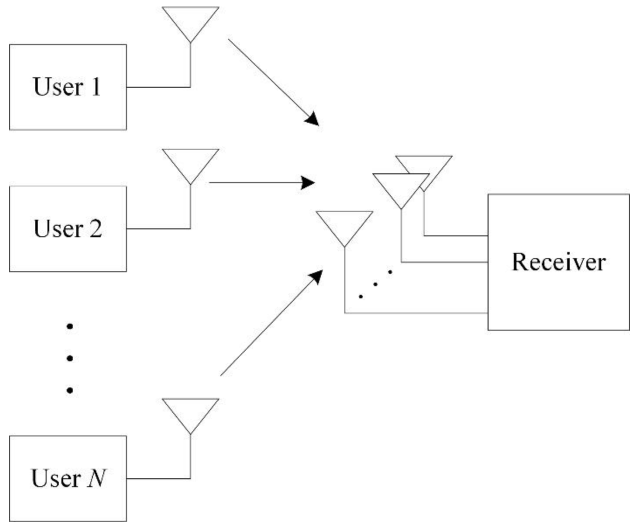


Figure 2. MPR techniques

➢ Research Background

Traditional *p*-persistent CSMA under **single-packet** reception (SPR)	Traditional *p*-persistent CSMA under **multiple-packet** reception (MPR)

Limitation 1	Early studies on *p*-persistent CSMA assumed the SPR model, which did not consider **the advance of MPR techniques**
Limitation 2	Further studies on *p*-persistent CSMA assumed the MPR model under the synchronous mode, which led to **bandwidth waste**
Limitation 3	Although some early studies have improved the protocol, they do not provide **a general analytical model**, and **the setting of access probabilities are far from the optimum**

➢ System Model

Carrier Sensing	We assume that **all users can perform carrier sensing** to detect if the number of ongoing transmissions is 0, ..., γ -1 or $\geq \gamma$, and the time required to do so is negligible.
Channel Assumption	We consider that **wireless fading effect is negligible**, and **channel coding is not used** to protect the packets.
γ-MPR Capability	We assume that the receiver has **the γ-MPR capability**, i.e., can recover all n signals simultaneously transmitted in a slot if $1 \leq n \leq \gamma$, and recover none of them otherwise.
Packet Length	We consider that the packet lengths correspond to **integer numbers of slots**, and follow **the geometric distribution** with average value $\Lambda>1$

➢ Main Contributions

Contrib. 1

Propose a generalized *p*-persistent CSMA for Asynchronous MPR

- System Model
- Protocol Design
- Example Analysis

Contrib. 2

Formulate such CSMA as a parameterized Markov decision process (MDP)

↓

Use the long-run average performance to evaluate the saturation throughput

Contrib. 3

Modify the MDP to obtain an upper bound on the throughput (Modification 1)

↓

State an important observation according to the above performance analysis

↓

Modify the MDP again and propose a heuristic design to achieve **the near-optimal throughput performance** (Modification 2)

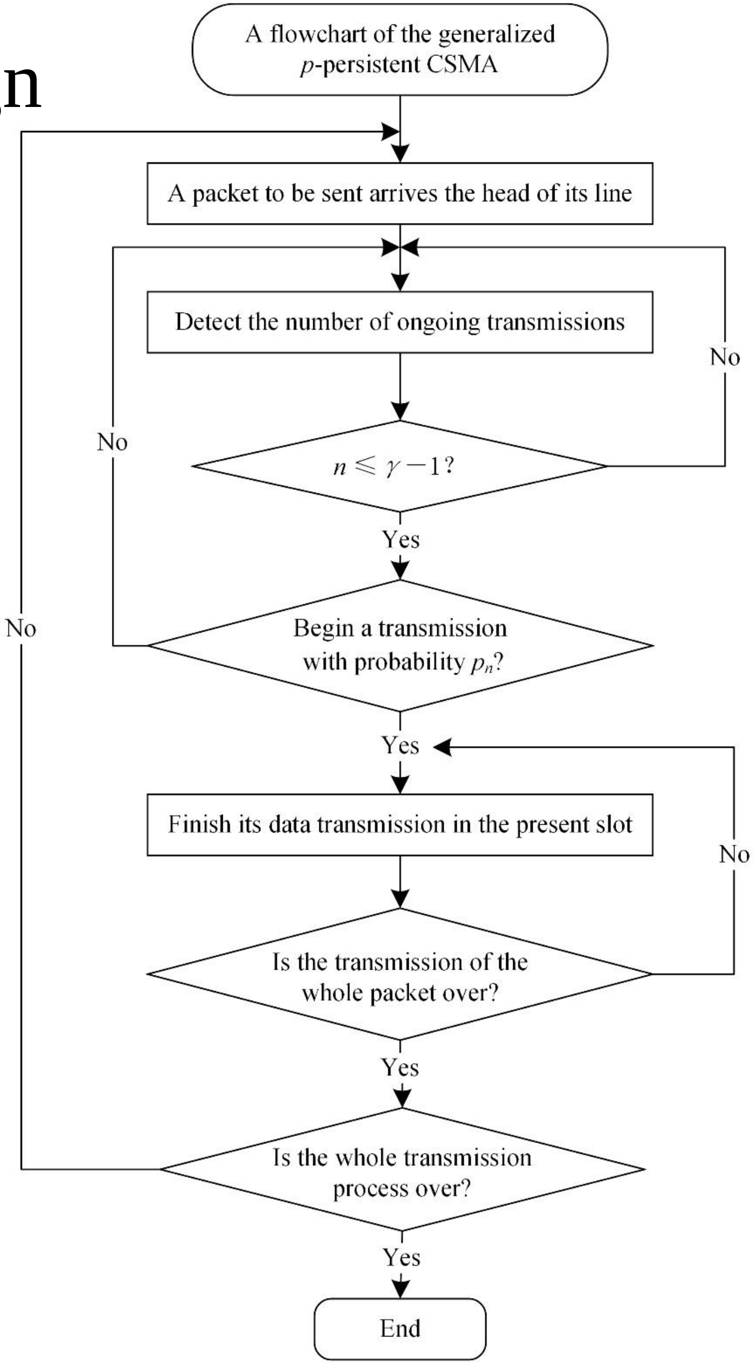
Contrib. 1 Protocol Design

Protocol Design

Each silent user is required to perform carrier sensing at the beginning of each time slot:

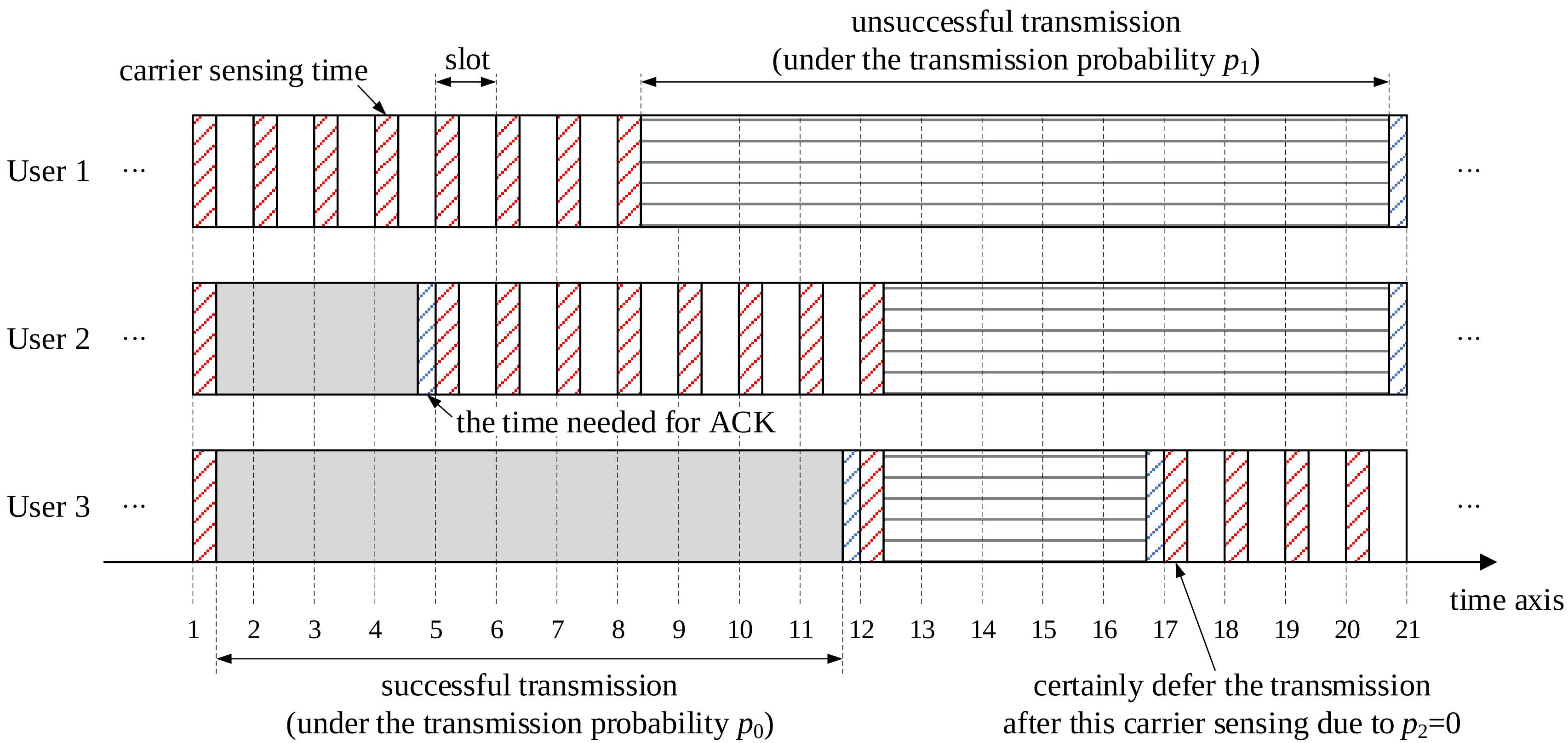
1. If this silent user detects $n < \gamma$ ongoing transmissions at the beginning of a slot, this user will begin a transmission with probability $0 \leq p_n < 1$;
2. Otherwise, this user will begin a transmission with probability $p_n = 0$.

Remark: The aforementioned system model with $\gamma = 1$ is exactly the model for *p*-persistent CSMA under SPR.



Contrib. 1 Protocol Design

- The generalized *p*-persistent CSMA for the case of $N = 3$ and $\gamma = 2$.



1. At the beginning of **slot 1**, **user 2** and **user 3** detect the number of ongoing transmission is **0**; thus they begin transmissions with probability $\boldsymbol{p_0}$.
2. At the beginning of **slot 8**, **user 1** detects the number of ongoing transmission is **1**; thus it begins a transmission with probability $\boldsymbol{p_1}$.

Contrib. 2 Protocol Analysis

Provide a general analytical model based on a parameterized MDP

Based on the access probability p_n, we define the parameter vector: $\mathbf{p} \triangleq (p_0, p_1, \ldots, p_{\gamma-1})$

↓

State	The ***state***, denoted by n, is defined as the number of ongoing transmissions in the carrier sensing phase.
Action	The ***action***, denoted by a, means that a users begin new transmissions after carrier sensing at state n.
Parameterized Policy	The ***parameterized policy***, denoted by $\pi_{n,a}(\mathbf{p})$, is defined as the probability that a out of $N - n$ users begin to transmit at state n.
Transition Probability	The ***transition probability***, denoted by $\varphi_{n,n'}(\mathbf{p})$, is defined as the probability that the next state is n' when the present state is n.
Reward → state	The ***state reward***, denoted by $r_n(\mathbf{p})$, is defined as the average of total packet lengths of all the successful transmissions at state n.
Reward → action	The ***action reward***, denoted by $r_{n,a}(\mathbf{p})$, is defined as the reward which is achieved when action a is taken at state n.

Contrib. 2 Protocol Analysis

Theoretical analysis of the state reward $r_n(\mathbf{p})$

We assume that a given packet is being transmitted in both the present and next slots.

$\xi_{h,h'}(\mathbf{p})$	The probability that there are *h*' other ongoing transmissions in the next slot when there have been *h* other ongoing transmissions in the present slot.

↓

$g_{m,h_1,h_m}(\mathbf{p})$	The probability that there are h_m other ongoing transmissions in the *m*-th slot of a given transmission, and fewer than γ other ongoing transmissions in each of the first *m*-1 slots of the transmission, provided that there are h_1 other ongoing transmissions in the first slot of the transmission.

↓

$q_{\lambda,h_1}(\mathbf{p})$	The probability that a λ-slot transmission is successful when there are fewer than γ other ongoing transmissions in each of the λ slots of the transmission

↓

$r_{n,a}(\mathbf{p})$ → $r_n(\mathbf{p})$ → Long-term average reward: $R(\mathbf{p}) \Rightarrow$ Throughput

Contrib. 3 Protocol Optimization

Definition of the optimization problem

Based on the access probability p_n, we define the parameter vector: $\mathbf{p} \triangleq (p_0, p_1, \dots, p_{\gamma-1})$

$\mathbf{p} \triangleq (p_0, p_1, \dots, p_{\gamma-1}) \subset \mathbb{D} \triangleq \mathbb{D}_0 \times \mathbb{D}_1 \times \cdots \times \mathbb{D}_{\gamma-1}$, where $\mathbb{D}_0 \in (0,1)$, $\mathbb{D}_n \in [0,1)$ $(n \geqslant 1)$

Throughtput $R(\mathbf{p})$ is a function of the parameter vector $\mathbf{p} \rightarrow \exists\ \mathbf{p} = \mathbf{p}_{opt} \Rightarrow R = R_{max}$

Define the optimization problem

$$\mathbf{p}_{opt} = \arg\max_{\mathbf{p} \in \mathbb{D}} R(\mathbf{p}), \quad R_{\max} = \max_{\mathbf{p} \in \mathbb{D}} R(\mathbf{p})$$

Contrib. 3 Protocol Optimization

Difficulties of the optimization problem

Search $\mathbb{D} \triangleq \mathbb{D}_0 \times \mathbb{D}_1 \times \cdots \times \mathbb{D}_{\gamma-1} \rightarrow$ Find the optimal $\mathbf{p}$ that maximizes $R(\mathbf{p})$

↓

Modern Optimization Algorithms (such as Genetic Algorithm)	The algorithms possibly takes a very long time to find the near-optimal $\mathbf{p}$, and are required to set opportune starting points.

Gradient-Based Methods	The term $q_{\lambda,h1}(\mathbf{p})$ in $r_n(\mathbf{p})$ is obtained recursively and the number of recursive steps increases with the geometrically distributed packet length. $\rightarrow$ The term $r_n(\mathbf{p})$ is difficult to be calculated.

A policy iteration type algorithm that optimizes a special category of parameterized MDPs

↓

Two Conditions	1. The state space can be partitioned such that the transition probabilities and rewards of all states are affected by a distinct parameter or none of parameters in $\mathbf{p}$. 2. The change of the parameters in $\mathbf{p}$ does not affect the conditional probability of the state value, known to be included in a partition.

Contrib. 3 Protocol Optimization

Difficulties of the optimization problem

Search $\mathbb{D} \triangleq \mathbb{D}_0 \times \mathbb{D}_1 \times \cdots \times \mathbb{D}_{\gamma-1}$ → Find the optimal $\mathbf{p}$ that maximizes R($\mathbf{p}$)

The First Condition of the Policy Iteration

The state space can be partitioned such that the transition probabilities and rewards of all states are affected by a distinct parameter or none of parameters in $\mathbf{p}$.

The Researched Parameterized MDP

1. The reward $r_0(\mathbf{p})$ is affected by all the parameters in $\mathbf{p}$
2. The reward $r_n(\mathbf{p})$ for $0 < n < \gamma$ is affected by all the parameters in $\mathbf{p}$ except p_0

MDP Modification

Mod. 1: Modify $r_n(\mathbf{p})$ to $r_n^*(\mathbf{p})$ and establish an upper bound on the throughtput → Obtain an important observation →

Mod. 2: Modify $r_n(\mathbf{p})$ to $r_n^{**}(\mathbf{p})$ and propose a heuristic design

➢ Contrib. 3 Protocol Optimization

➢ Mod. 1: Establish an upper bound on the throughtput

Reward $r_n(\mathbf{p})$	The reward, denoted by $r_n(\mathbf{p})$, is defined as the average of total packet lengths of all the successful transmissions at state n.
Reward $r_n^*(\mathbf{p})$	The reward, denoted by $r_n^*(\mathbf{p})$, is defined as the average of total packet lengths of the transmissions, each of which is begun at state n, and received successfully at the first slot of its transmission. $\rightarrow r_n^*(\mathbf{p}) = \Lambda \sum_{a=0}^{\gamma-n} a \cdot \pi_{n,a}(p_n) \rightarrow R^*(\mathbf{p}) = \sum_{n=0}^{\gamma-1} \mu_n(\mathbf{p}) r_n^*(\mathbf{p})$ → Satisfy the first condition of the policy iteration

The packets overlap with $\gamma - 1$ or fewer other packets at the first slot of its transmission.

Definition of The Optimization Problem	$\mathbf{p}_{upp} = \arg\max_{\mathbf{p}\in\mathbb{D}} R^*(\mathbf{p}),\ R_{upp} = \max_{\mathbf{p}\in\mathbb{D}} R^*(\mathbf{p})$

➢ Contrib. 3 Protocol Optimization

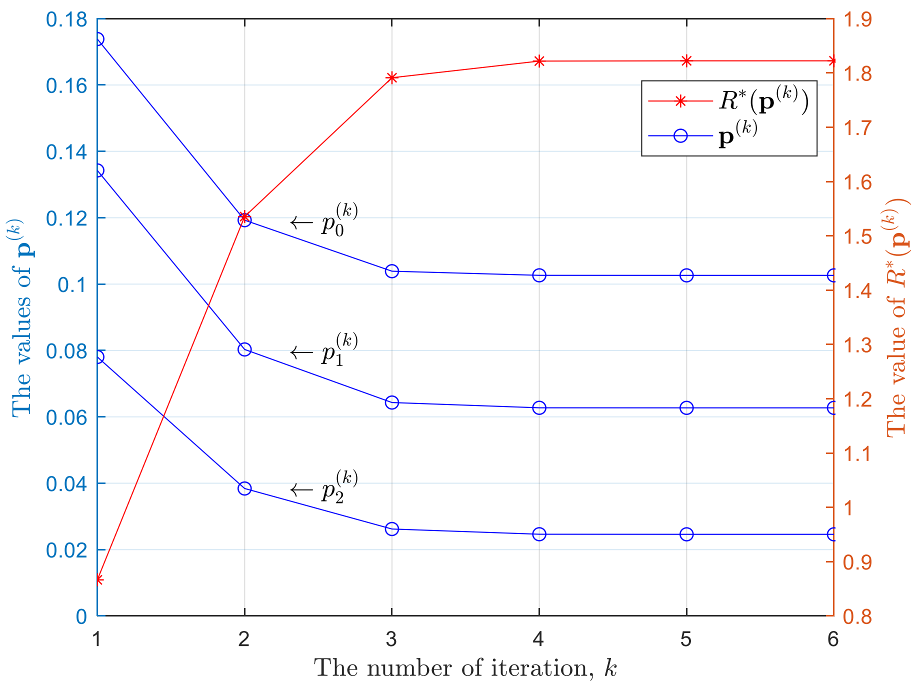
➢ Mod. 1: Solve $\mathbf{p}_{upp}$ by the policy iteration (**Algorithm 1**)

1. Initialization	Choose an arbitrary parameter vector $\mathbf{p}^{(0)} \subset \mathbb{D}$ as the initial value and set $k = 0$.
2. Evaluation	Calculate the relative value $v_n^*\left(\mathbf{p}^{(k)}\right)$ for each $n \in \mathcal{S}$ by Bellman equation.
3. Improvement	For $n = 0,1, \ldots, \gamma - 1$, update the new parameter as: $p_n^{(k+1)} = \arg\max_{p_n \in \mathbb{D}} r_n^*(p_n) + \sum_{n' \in \mathcal{S}} \phi_{n,n'}(p_n) v_{n'}^*(\mathbf{p}^{(k)})$
4. Stopping Rule	If $\mathbf{p}^{(k+1)} = \mathbf{p}^{(k)}$, set $\mathbf{p}_{upp} = \mathbf{p}^{(k)}$ and stop. Otherwise, set $k = k + 1$ and go to step 2.

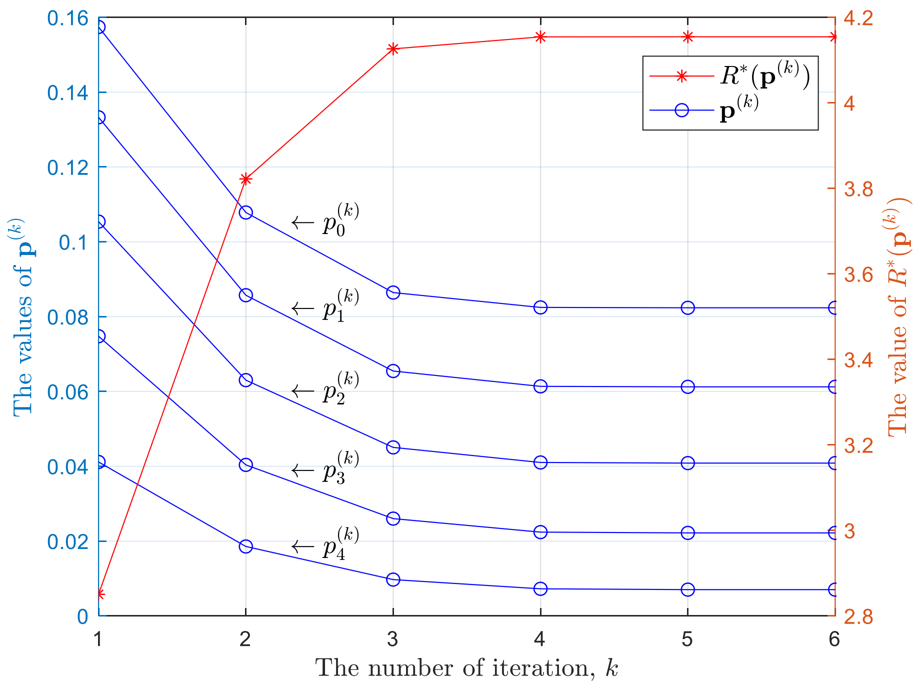
➤ Contrib. 3 Protocol Optimization

➤ Mod. 1: The iteration procedure of the parameters **p** and $R^*(\mathbf{p})$

Parameters: N=10, γ=3, Λ=20



Parameters: N=20, γ=5, Λ=50



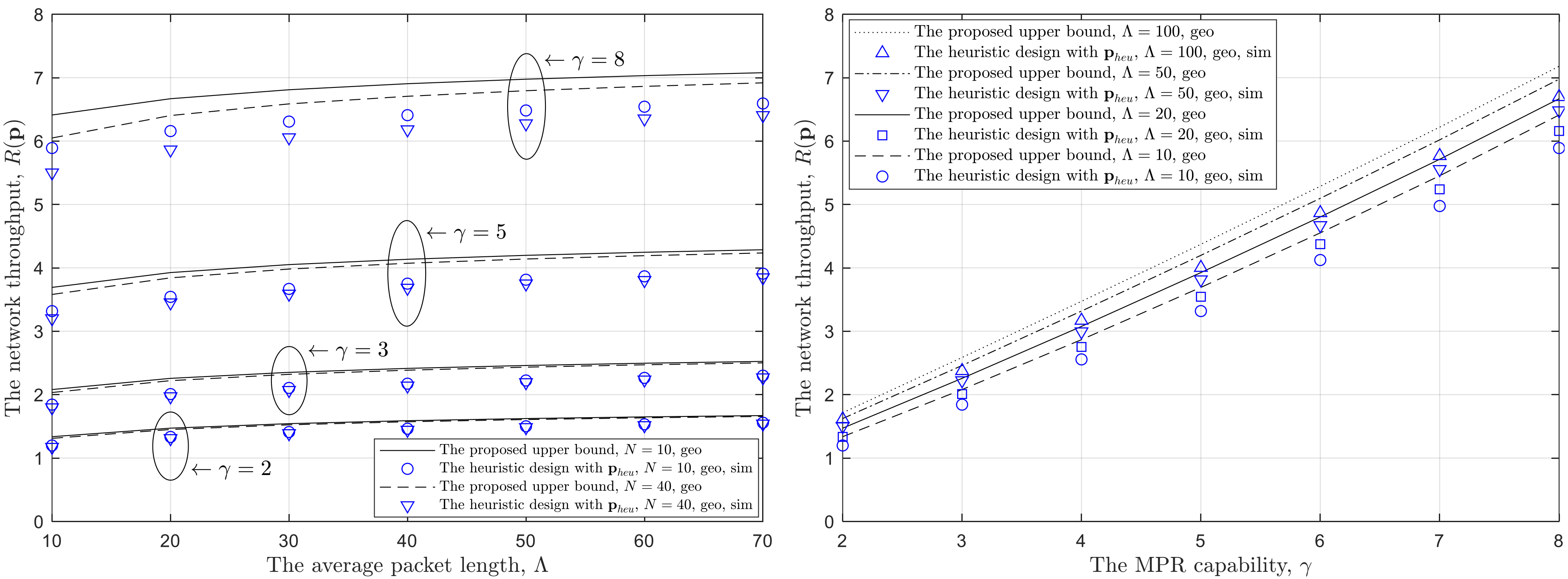
***Initialization*:** We set $p_0^{(k)} = \gamma/N$, and $p_n^{(k)} = 0$ for $1 \leq n \leq \gamma - 1$.

***Conclusion*:** It can be seen that only **6 iterations** are needed to satisfy the stopping rule.

➢ Contrib. 3 Protocol Optimization

➢ Mod 1: Comparisons between the throughput and its upper bound

***Remark*:** We set the maximum number of allowed retransmissions to be infinitely large.



***Conclusion*:** Relative gaps between the throughput performance and its upper bound are significant correlation with the parameter Λ and the parameter γ

➢ Contrib. 3 Protocol Optimization

➢ Mod. 2: Propose of the heuristic design

Reward $r_n(\mathbf{p})$	The reward, denoted by $r_n(\mathbf{p})$, is defined as the average of total packet lengths of all the successful transmissions at state n.
Reward $r_n^{**}(\mathbf{p})$	(I) If $n \geq \gamma$, no reward is gained. (II) If $n < \gamma$ and $0 \leq a \leq \gamma - n$, the total packet lengths of these a new transmissions are regarded as the positive reward. (III) If $n < \gamma$ and $\gamma - n < a \leq N - n$, no positive reward is gained and the total packet lengths of the n ongoing transmissions in the carrier sensing phase are regarded as the negative reward. $\rightarrow r_n^{**}(\mathbf{p}) = \Lambda \sum_{a=0}^{\gamma-n} a \cdot \mu_{n,a}(p_n) - 2n\Lambda \sum_{a=\gamma-n+1}^{N-n} \mu_{n,a}(p_n)$ $\rightarrow R^{**}(\mathbf{p}) = \sum_{n=0}^{\gamma-1} \mu_n(\mathbf{p}) r_n^{**}(\mathbf{p})$ → Satisfy the first condition of the policy iteration
Observation	When the system operates with $\mathbf{p}$ whose values are close to $\mathbf{p}_{\text{opt}}$, there is a small probability that a transmission suffers from **severe conflict**.
Severe Conflict	If a given transmission collides with new transmissions at more than one slot, we say this transmission suffers from severe conflict.

Contrib. 3 Protocol Optimization

Mod. 2: Propose of the heuristic design

Reward $r_n(\mathbf{p})$	The reward, denoted by $r_n(\mathbf{p})$, is defined as the average of total packet lengths of all the successful transmissions at state n.
Reward $r_n^{**}(\mathbf{p})$	(I) If $n \geq \gamma$, no reward is gained. (II) If $n < \gamma$ and $0 \leq a \leq \gamma - n$, the total packet lengths of these a new transmissions are regarded as the positive reward. (III) If $n < \gamma$ and $\gamma - n < a \leq N - n$, no positive reward is gained and the total packet lengths of the n ongoing transmissions in the carrier sensing phase are regarded as the negative reward. $\rightarrow r_n^{**}(\mathbf{p}) = \Lambda \sum_{a=0}^{\gamma-n} a \cdot \mu_{n,a}(p_n) - 2n\Lambda \sum_{a=\gamma-n+1}^{N-n} \mu_{n,a}(p_n)$ $\rightarrow R^{**}(\mathbf{p}) = \sum_{n=0}^{\gamma-1} \mu_n(\mathbf{p}) r_n^{**}(\mathbf{p})$ $\rightarrow$ Satisfy the first condition of the policy iteration

Definition of The Optimization Problem	$\mathbf{p}_{heu} = \arg\max_{\mathbf{p}\in\mathbb{D}} R^{**}(\mathbf{p}),\ R_{heu} = \max_{\mathbf{p}\in\mathbb{D}} R(\mathbf{p}_{heu})$

➢ Contrib. 3 Protocol Optimization

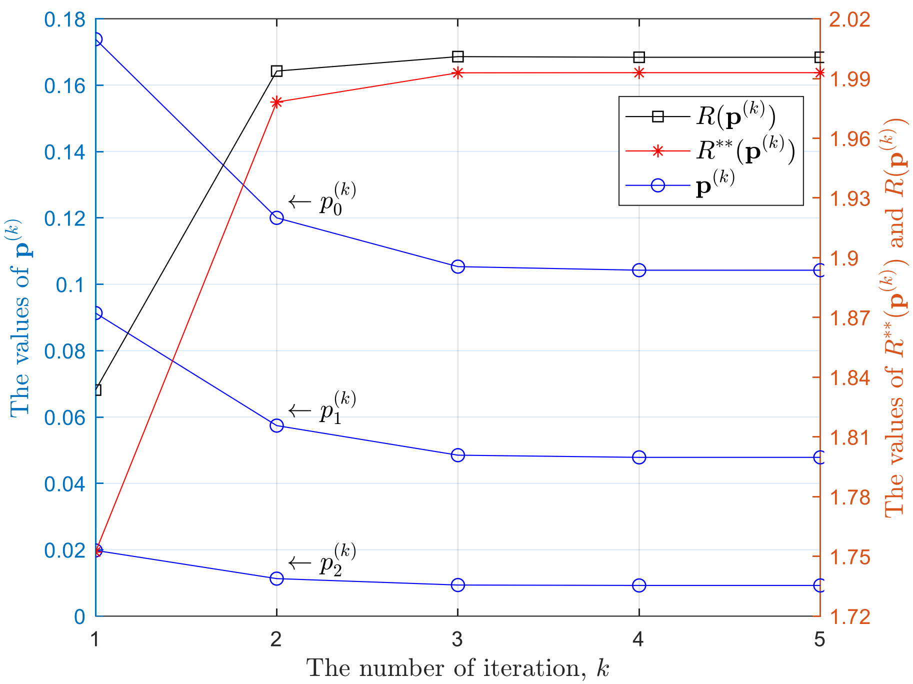
➢ Mod. 2: Solve $\mathbf{p}_{heu}$ by the policy iteration (**Algorithm 2**)

1. Initialization	Choose an arbitrary parameter vector $\mathbf{p}^{(0)} \subset \mathbb{D}$ as the initial value and set $k = 0$.
2. Evaluation	Calculate the relative value $v_n^*(\mathbf{p}^{(k)})$ for each $n \in \mathcal{S}$ by Bellman equation.
3. Improvement	For $n = 0,1, \dots, \gamma - 1$, update the new parameter as: $p_n^{(k+1)} = \arg\max_{p_n \in \mathbb{D}} r_n^{**}(p_n) + \sum_{n' \in \mathcal{S}} \phi_{n,n'}(p_n) v_{n'}^{**}(\mathbf{p}^{(k)})$
4. Stopping Rule	If $\mathbf{p}^{(k+1)} = \mathbf{p}^{(k)}$, set $\mathbf{p}_{upp} = \mathbf{p}^{(k)}$ and stop. Otherwise, set $k = k + 1$ and go to step 2.

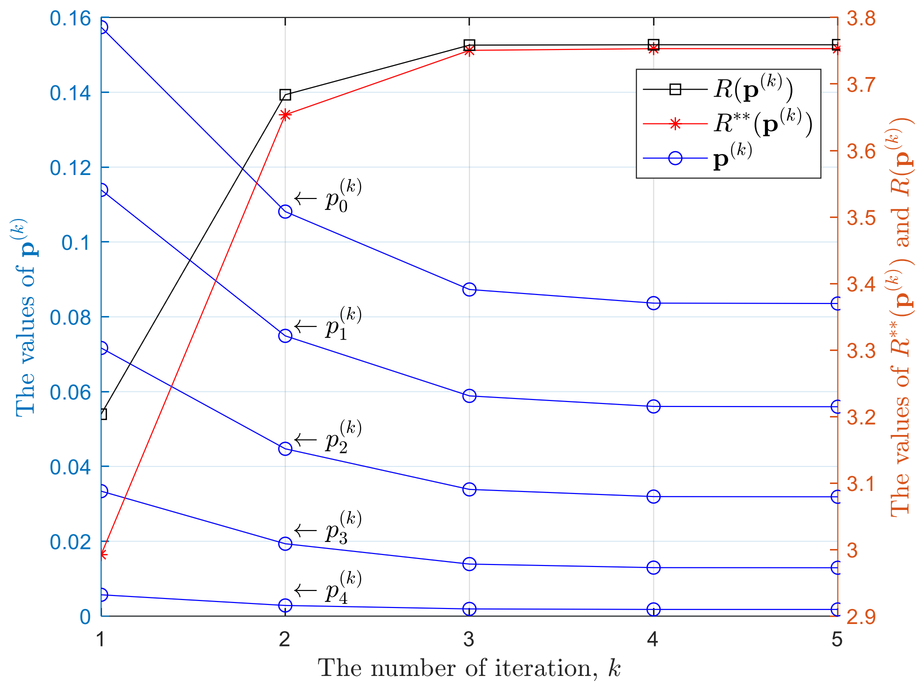
➢ Contrib. 3 Protocol Optimization

➢ Mod. 2: The iteration procedure of the parameters **p** and $R^*(\mathbf{p})$

Parameters: N=10, γ=3, Λ=20



Parameters: N=20, γ=5, Λ=50



***Initialization*:** We set $p_0^{(k)} = \gamma/N$, and $p_n^{(k)} = 0$ for $1 \le n \le \gamma - 1$.

***Conclusion*:** It can be seen that only **5 iterations** are needed to satisfy the stopping rule.

➢ Contrib. 3 Protocol Optimization

➢ Mod 2: Comparisons between the heuristic design and *GlobalSearch (GS)*

The GS Solve (in *MATLAB Optimization Toolbox*) can be used to find global minima.

N	Algorithm	Time	p_0	p_1	p_2	p_3	p_4	*R*
10	***GS Solve***	**4297.92s**	0.22079	0.16006	0.09995	0.04517	0.00699	3.5353
	Heuristic Design	**18.77s**	0.22127	0.15934	0.09869	0.04402	0.00655	3.5348
12	***GS Solve***	**2991.38s**	0.17681	0.12568	0.07676	0.03384	0.00509	3.5090
	Heuristic Design	**24.17s**	0.17711	0.12505	0.07574	0.03295	0.00476	3.5085
14	***GS Solve***	**2886.17s**	0.14766	0.10358	0.06237	0.02708	0.00401	3.4928
	Heuristic Design	**30.28s**	0.14786	0.10303	0.06152	0.02635	0.00374	3.4923
16	***GS Solve***	**5758.00s**	0.12683	0.08814	0.05254	0.02257	0.00331	3.4818
	Heuristic Design	**43.00s**	0.12698	0.08765	0.05181	0.02196	0.00309	3.4813
18	***GS Solve***	**19283.63s**	0.11120	0.07673	0.04540	0.01936	0.00281	3.4738
	Heuristic Design	**85.78s**	0.11131	0.07629	0.04476	0.01883	0.00263	3.4733
20	***GS Solve***	**29465.91s**	0.09901	0.06795	0.03998	0.01694	0.00245	3.4678
	Heuristic Design	**86.02s**	0.09910	0.06754	0.03941	0.01648	0.00228	3.4672

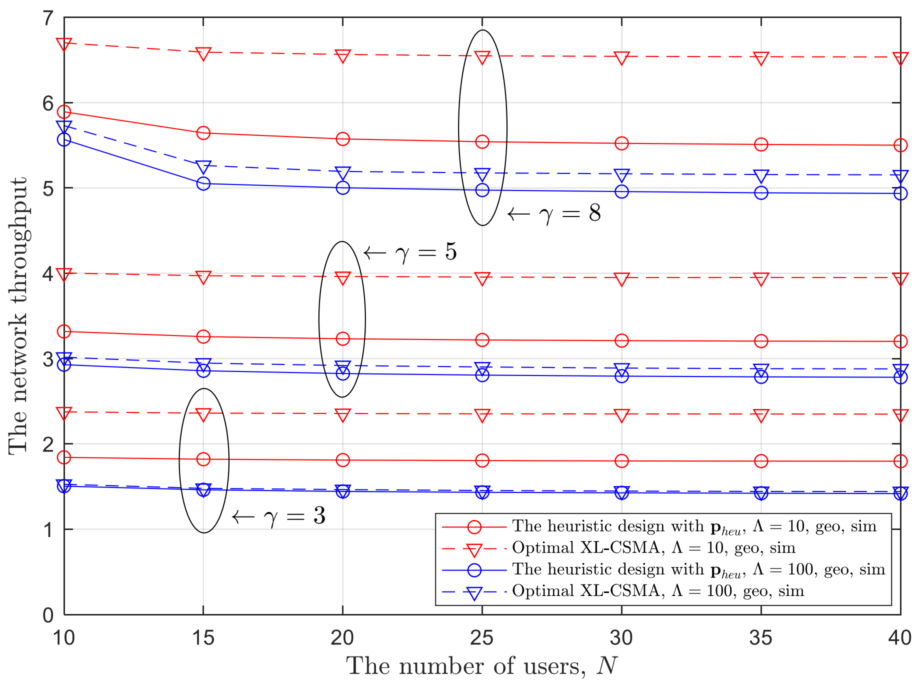
Conclusion: The near-optimal parameter vectors and throughtput solved in the heuristic design are basically the same as the optimal results solved by “GlobalSearch”.

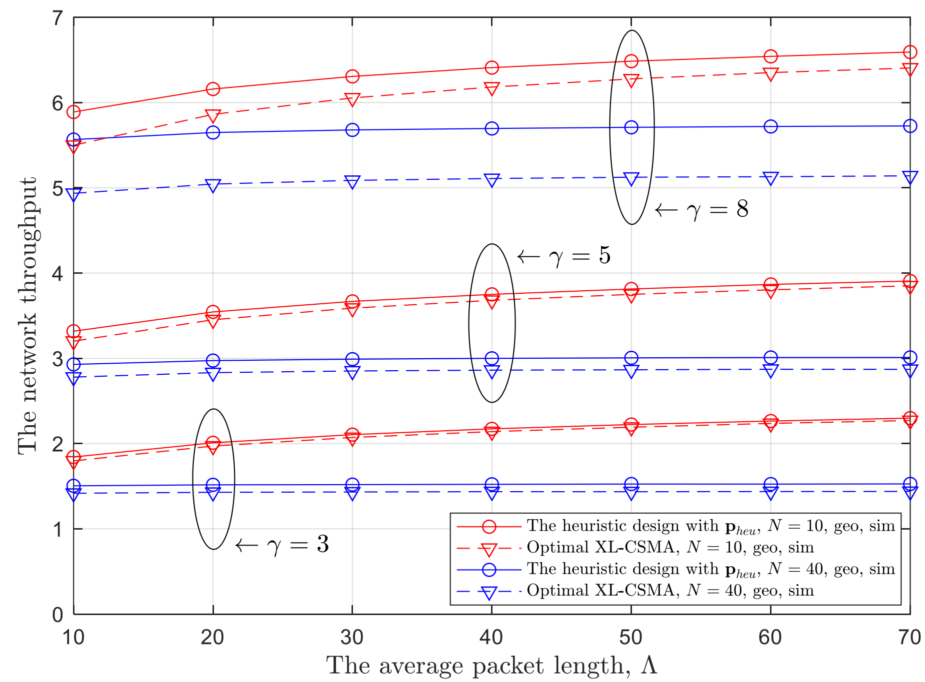
➢ Contrib. 3 Protocol Optimization

➢ Mod 2: Comparisons between the heuristic design and XL-CSMA

***Remark*:** We set the maximum number of allowed retransmissions to be infinitely large.

XL-CSMA	Each user adopts the access probabilities $p_n = \max(0, (\gamma^* - n) / (N - n))$ for $n = 0, 1, \ldots, \gamma - 1$, where the tuning parameter $\gamma*$ is an integer not larger than γ.





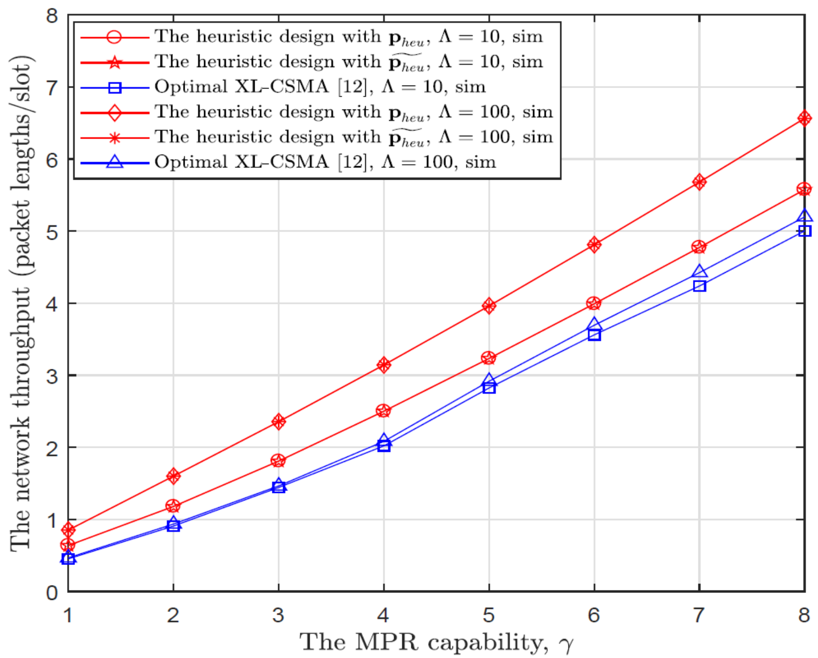
Conclusion: The heuristic design **significantly outperforms** optimal XL-CSMA in all the cases.

Contrib. 3 Protocol Optimization

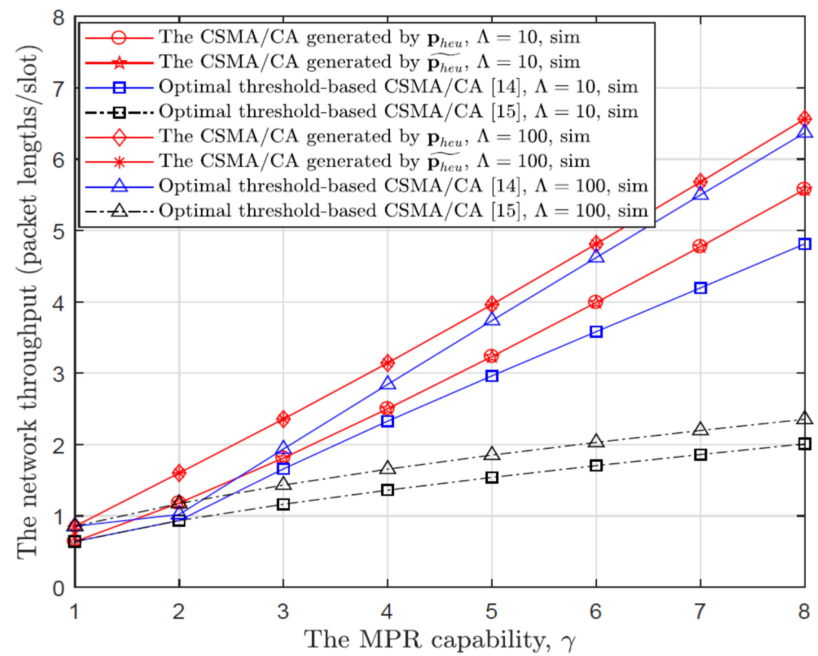
Mod 2: Convert the generalized *p*-persistent CSMA to a CSMA/CA

***Remark*:** We set the maximum number of allowed retransmissions to 4.

Convert to CSMA/CA	To convert the generalized *p*-persistent CSMA to a CSMA/CA scheme for IEEE 802.11-like networks, we require each user to maintain **contention window *n*** with the constant size $W_n = \lfloor 2/p_n - 1 \rfloor$ if $p_n > 0$ for $n = 0, 1, \ldots, c-1$.



The Generalized *p*-persistent CSMA



The Converted CSMA/CA