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École Mines-Télécom

Radio Channel Blacklisting in IEEE 802.15.4

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Problem Formulation

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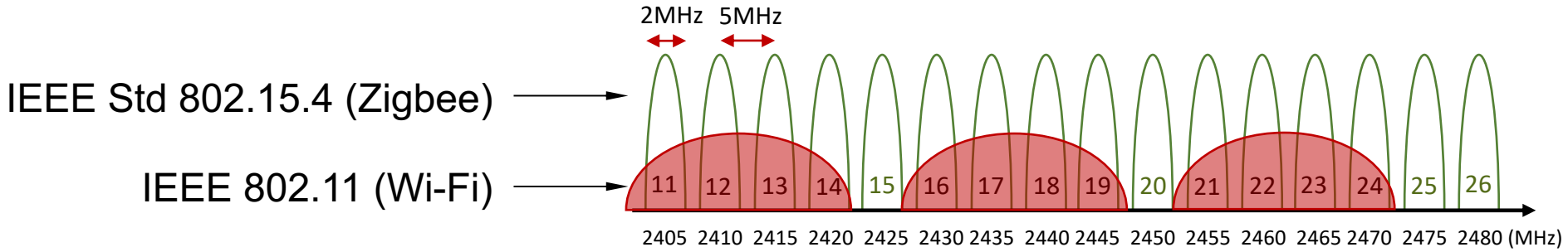
Problem Formulation

Is Blacklisting a Relevant Strategy in TSCH to improve the PDR?

- The continues growth of wireless technologies that operate over the 2.4GHz such as Wi-Fi, Bluetooth Low Energy (BLE), Zigbee:
  - Causing intra- and inter-technology interference.



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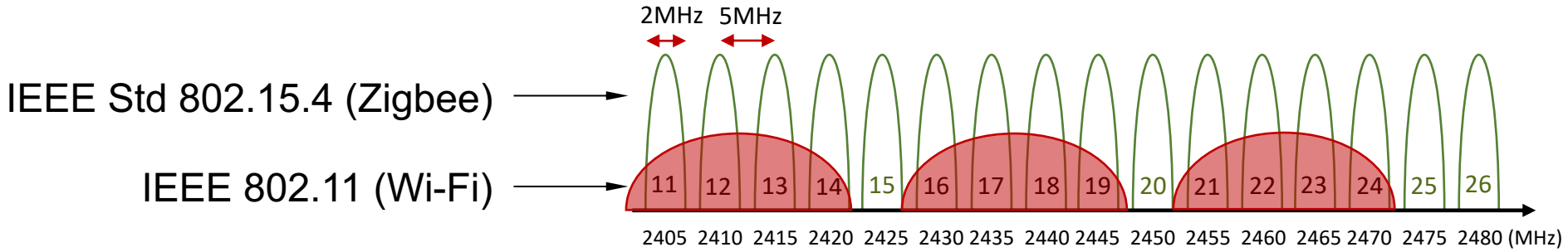
- The Wi-Fi networks represent a “threat” to Zigbee and BLE systems:
  - High transmission power.
  - Massive spectrum occupancy (bande passante du canal).



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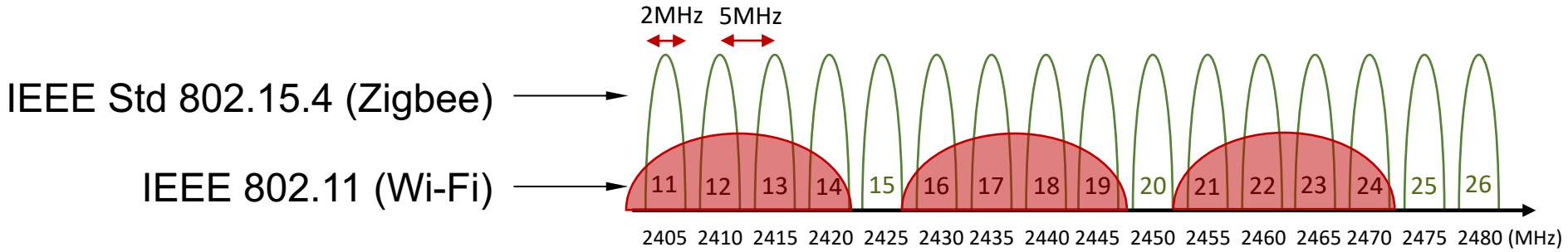
What about Radio Channel Blacklisting Technique?
- External interference
- Multi-path fading



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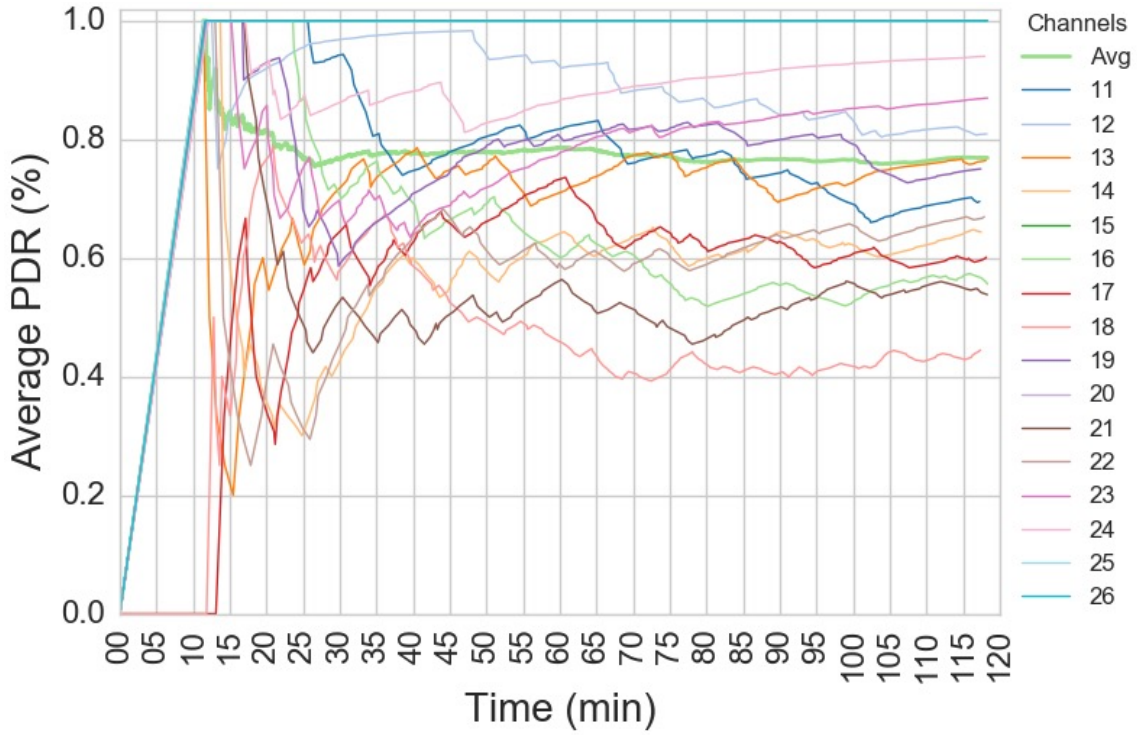
  - Detecting the “poor” radio channels, e.g., radio channels below 50% of PDR.



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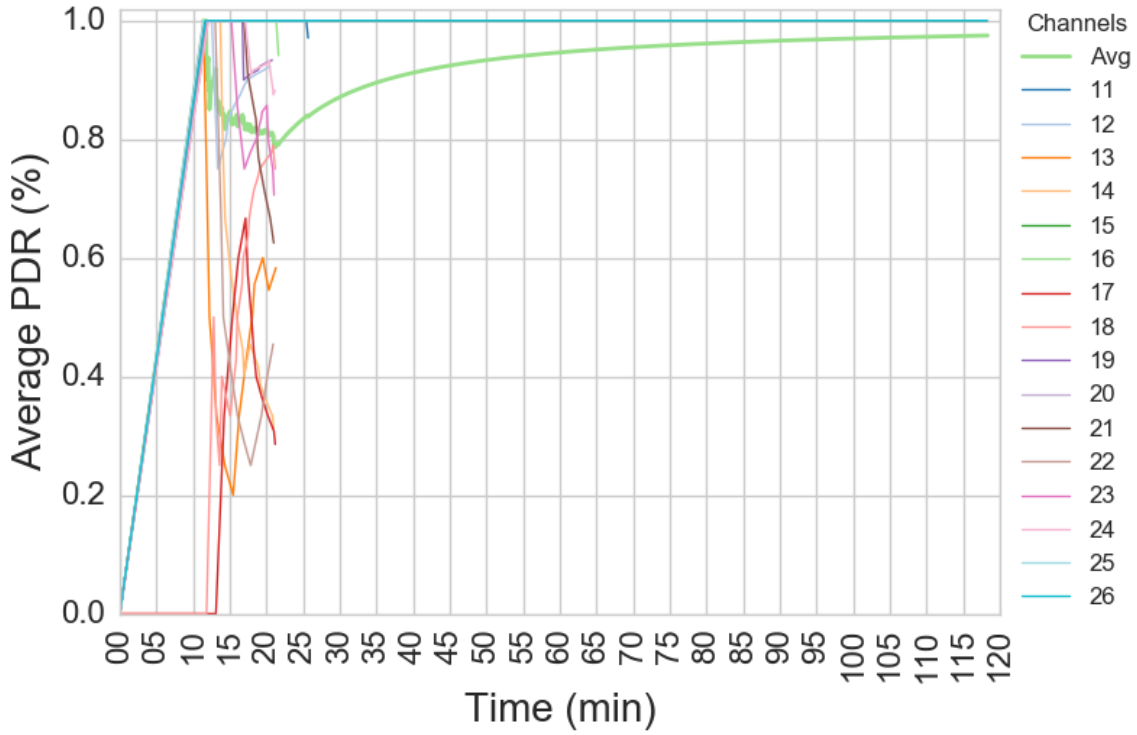

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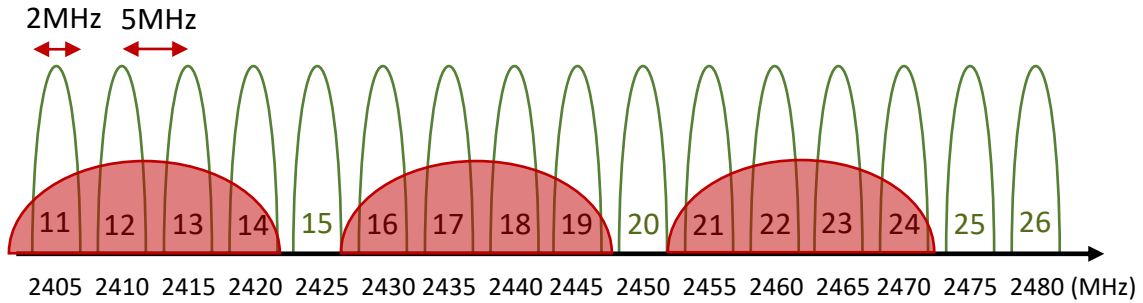
  - Thus, number of radio channels (***$N_{channels}$***) to use will be **reduced** from total 16.

$$Radio\ Channel = F[(ASN + chOffset)\%N_{channels}]$$



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There’s no such thing as a Free Lunch!
- Throughput (network capacity)

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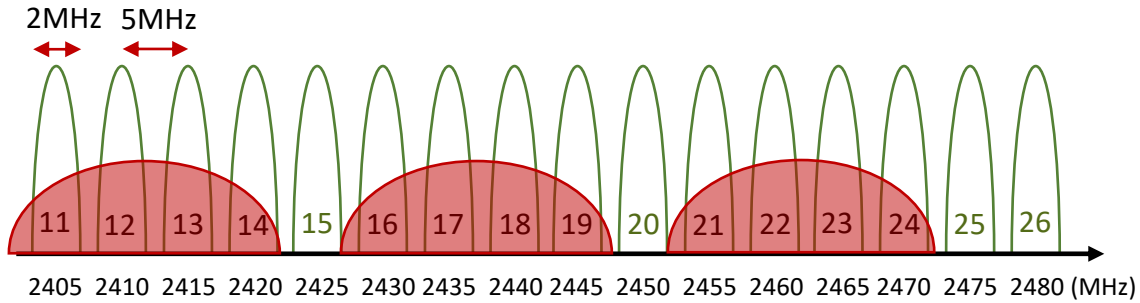

Radio Characterization

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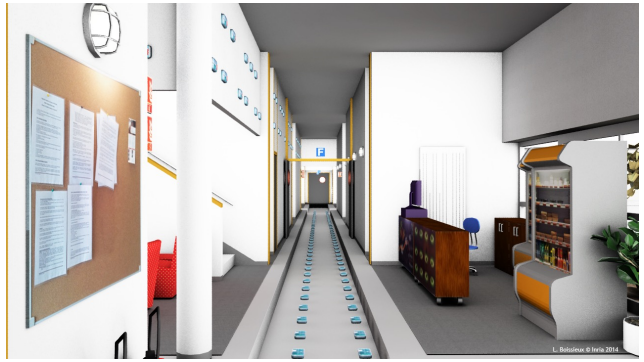
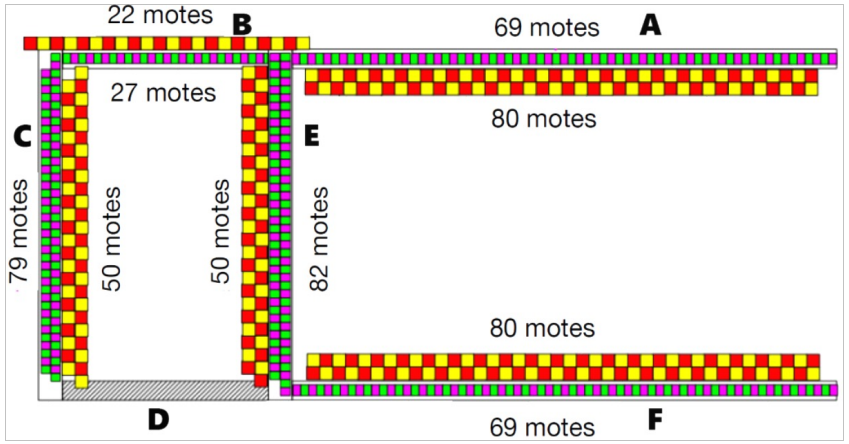
Radio Characterization
FIT IoT-LAB

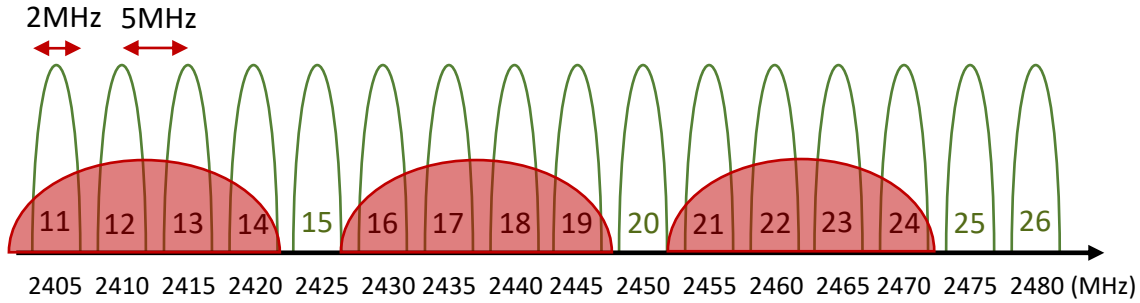
- Investigate the radio spectrum characteristics:
  - FIT IoT-LAB platform, Grenoble testbed.
  - Many Wi-Fi Access Points are deployed.



FIT IoT-LAB: *Grenoble's site*

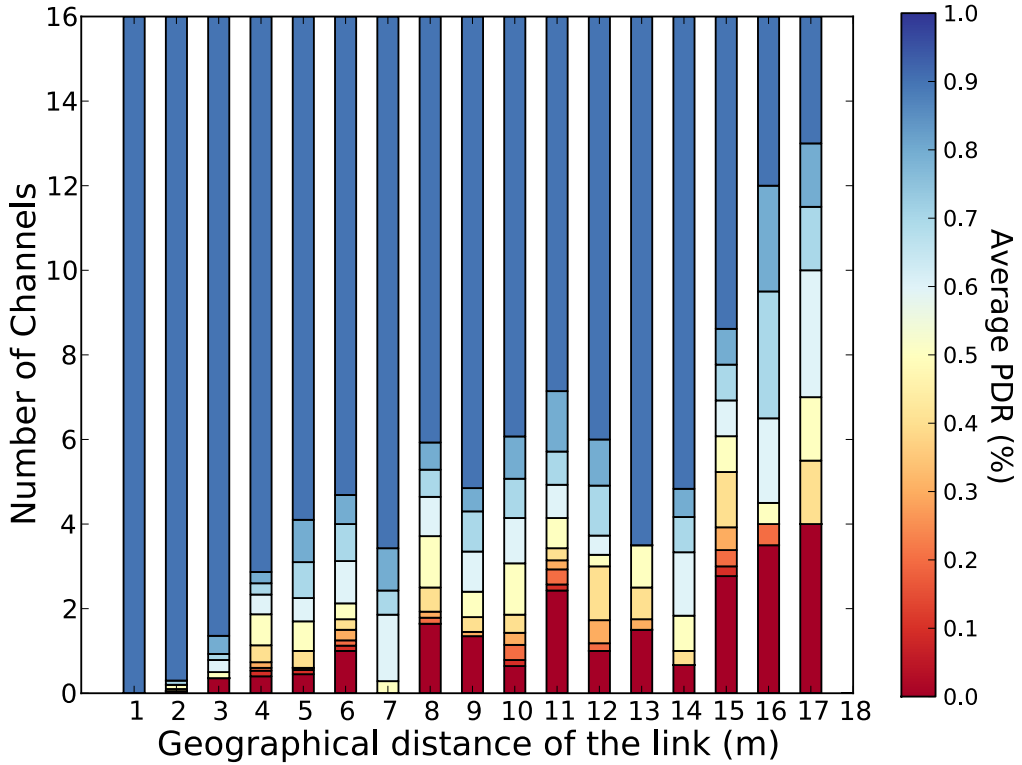


Parameter	Value
# of nodes	2
Nodes spacing	0.6 - 17 *m*
Duration	90 *min*
# of experiments	*200*
Application model	1 *pkt / 3 sec*



Radio Characterization
Distance Variability

- The quality of the radio links is:
  - Distance-dependent.



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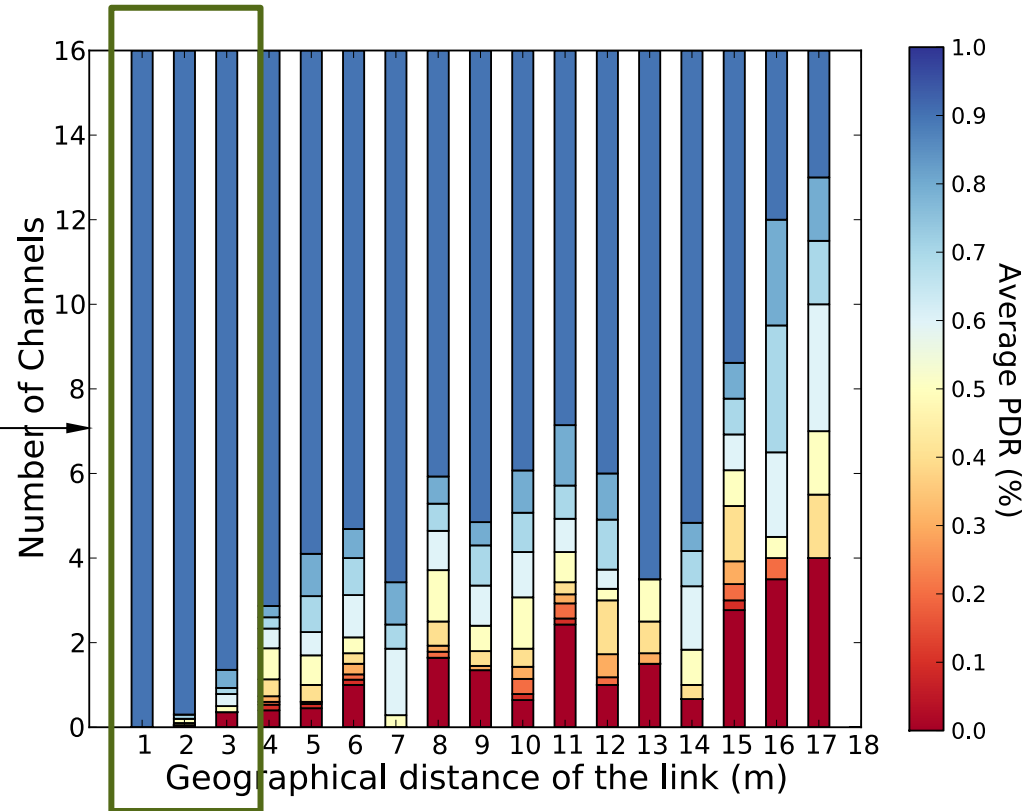
Short link distances →
Higher quality performance.



Radio Characterization

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Long link distances →
Dynamic behavior.

Short link distances →
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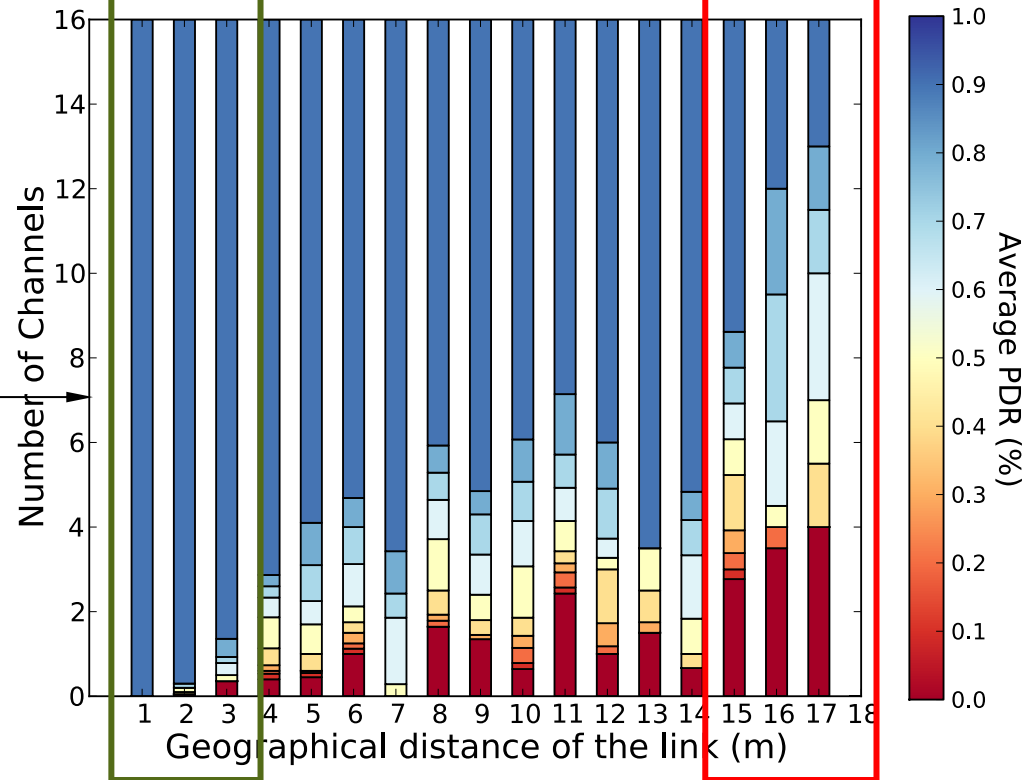

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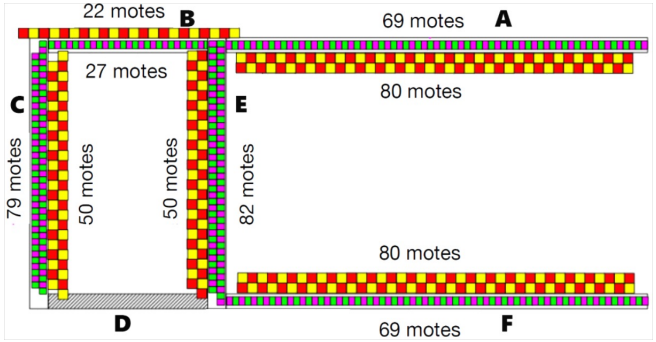

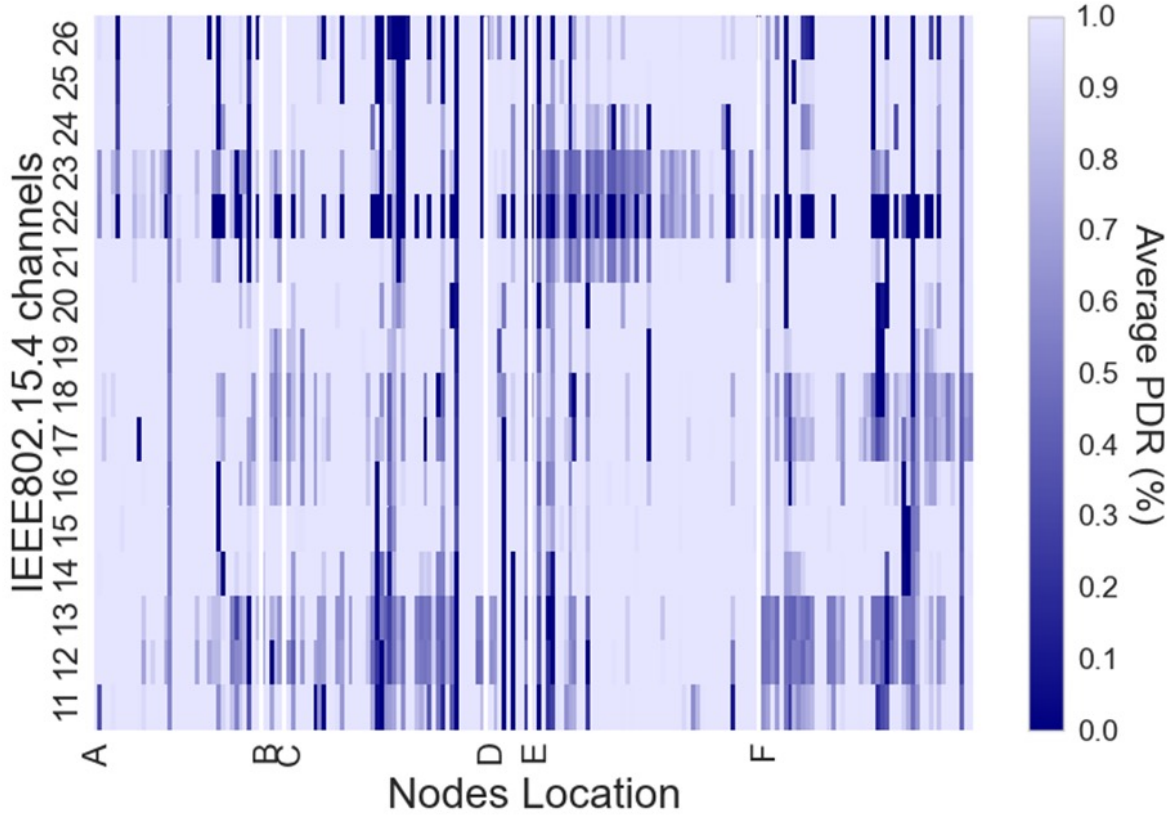

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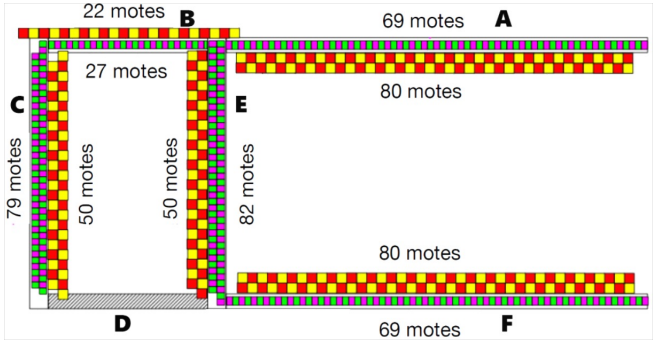
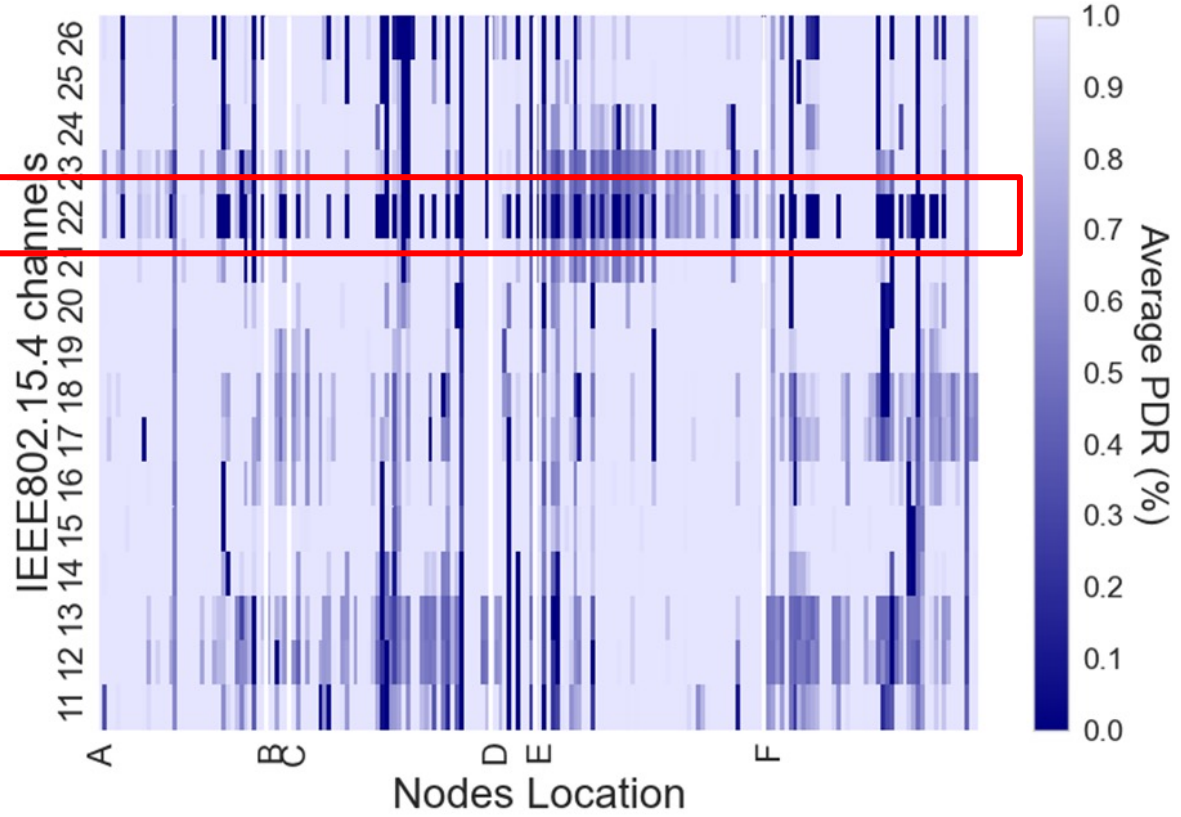


Bad radio channels for many links



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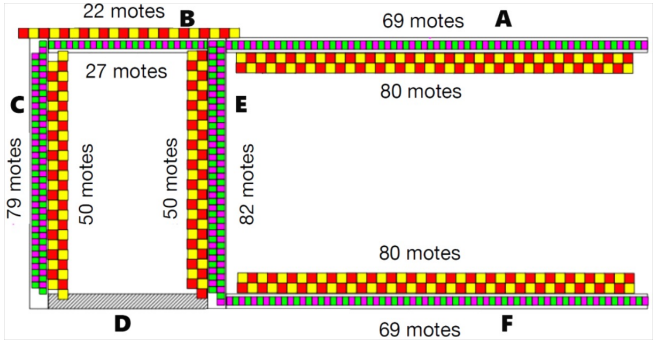
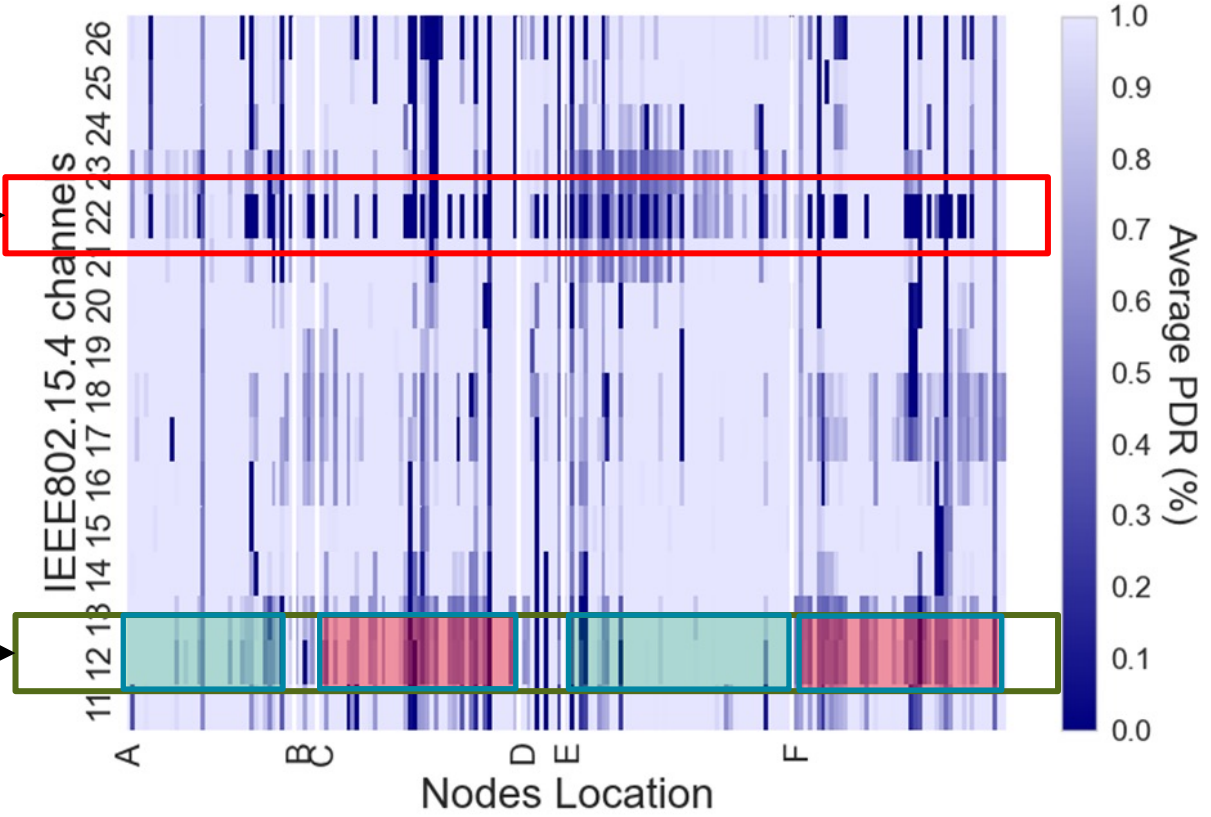


Bad radio channels for many links

Specific local patterns (corridors CF & AE)



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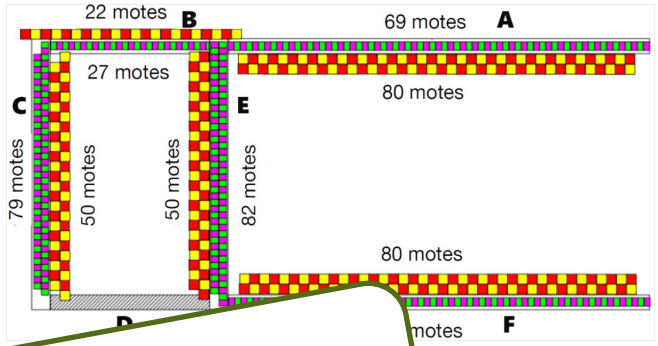
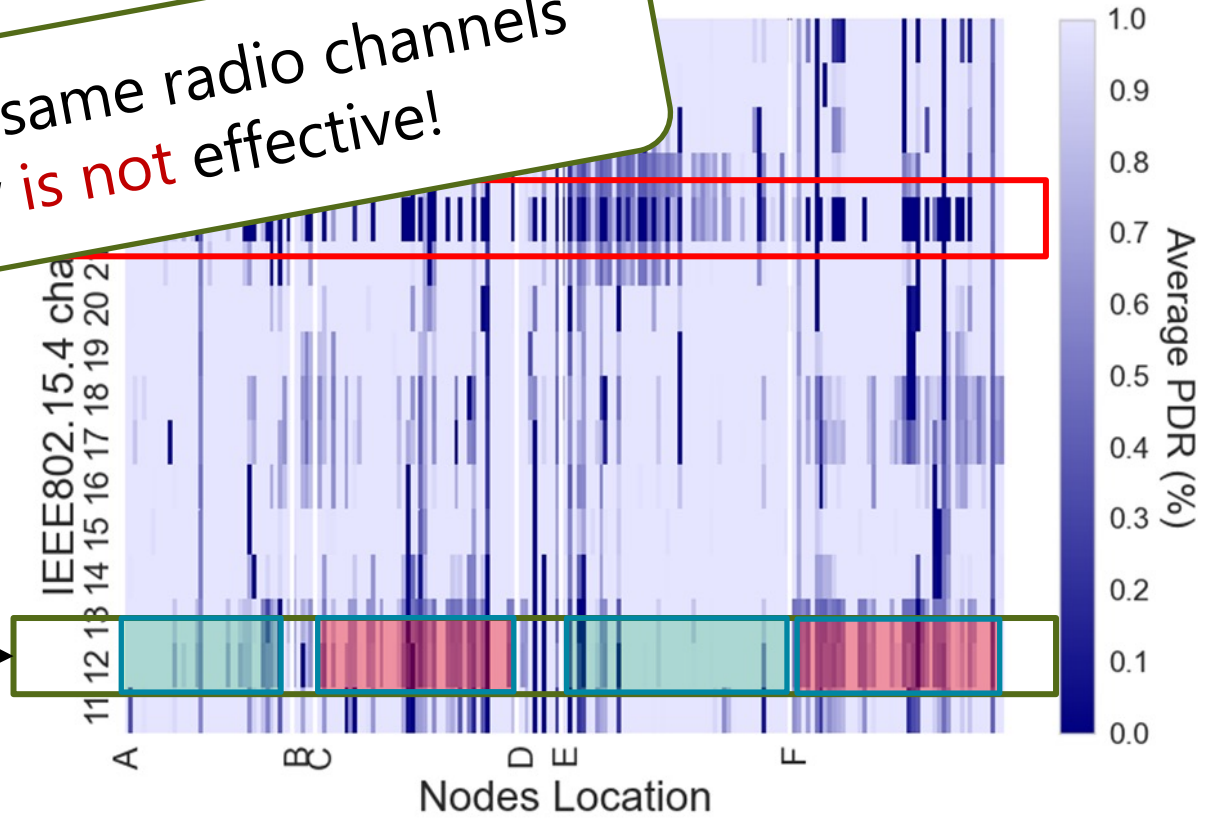


Bad radio channels fo

Excluding the same radio channels **Globally** is not effective!



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Radio Characterization

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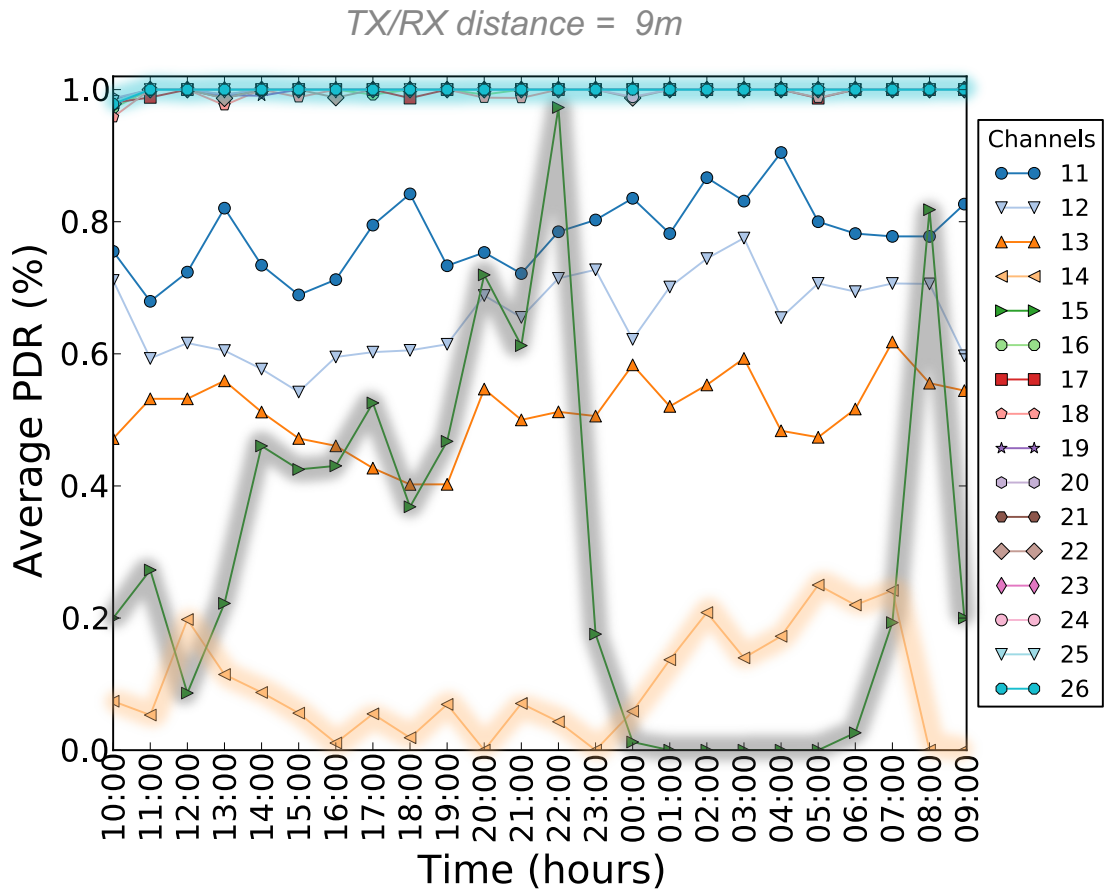

Radio Characterization

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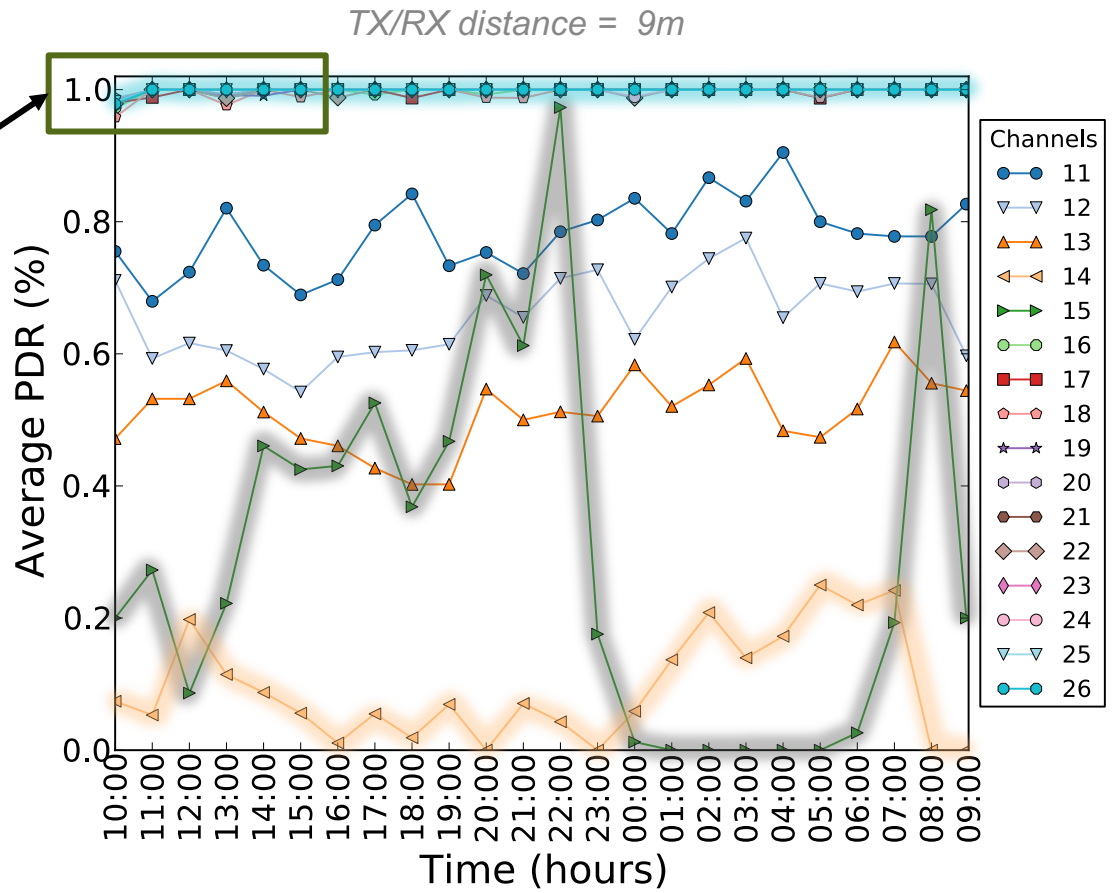
Perform well, and are very stable, e.g., radio channel 26.



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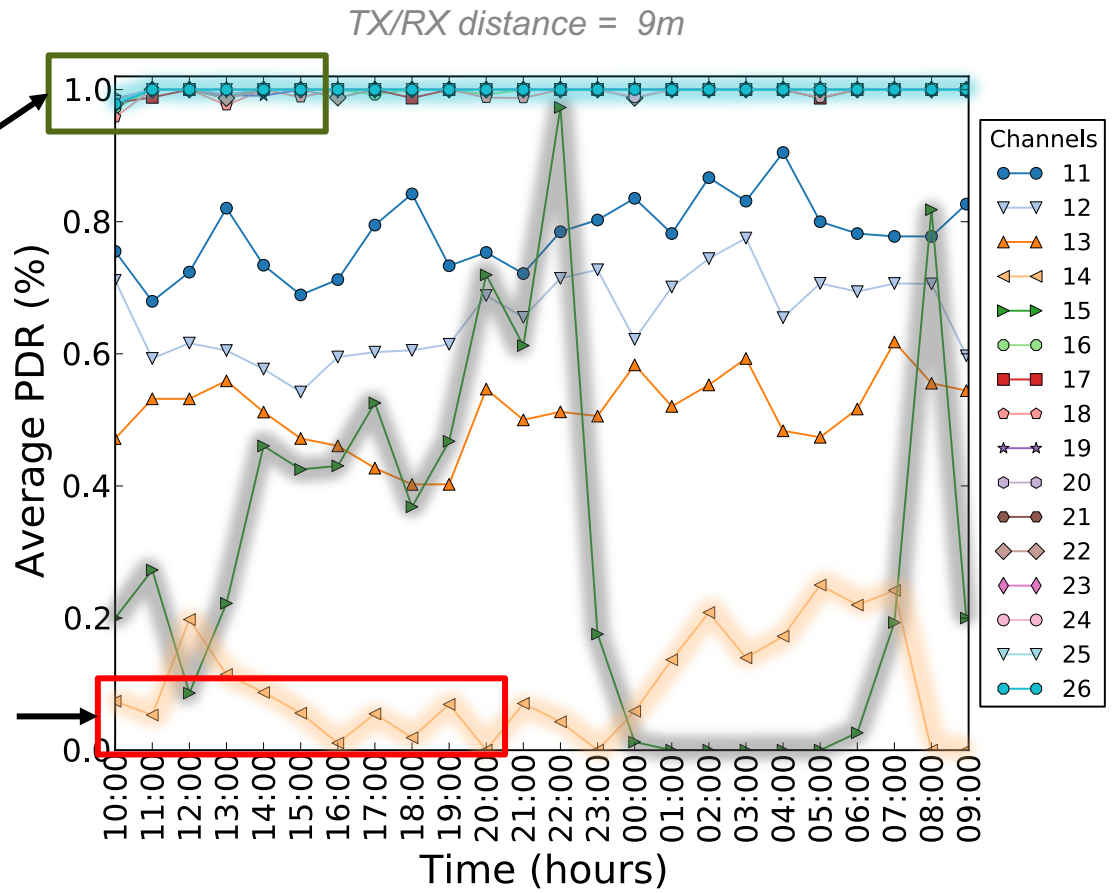

Always bad, e.g., radio channel 14 → **blacklist** it!

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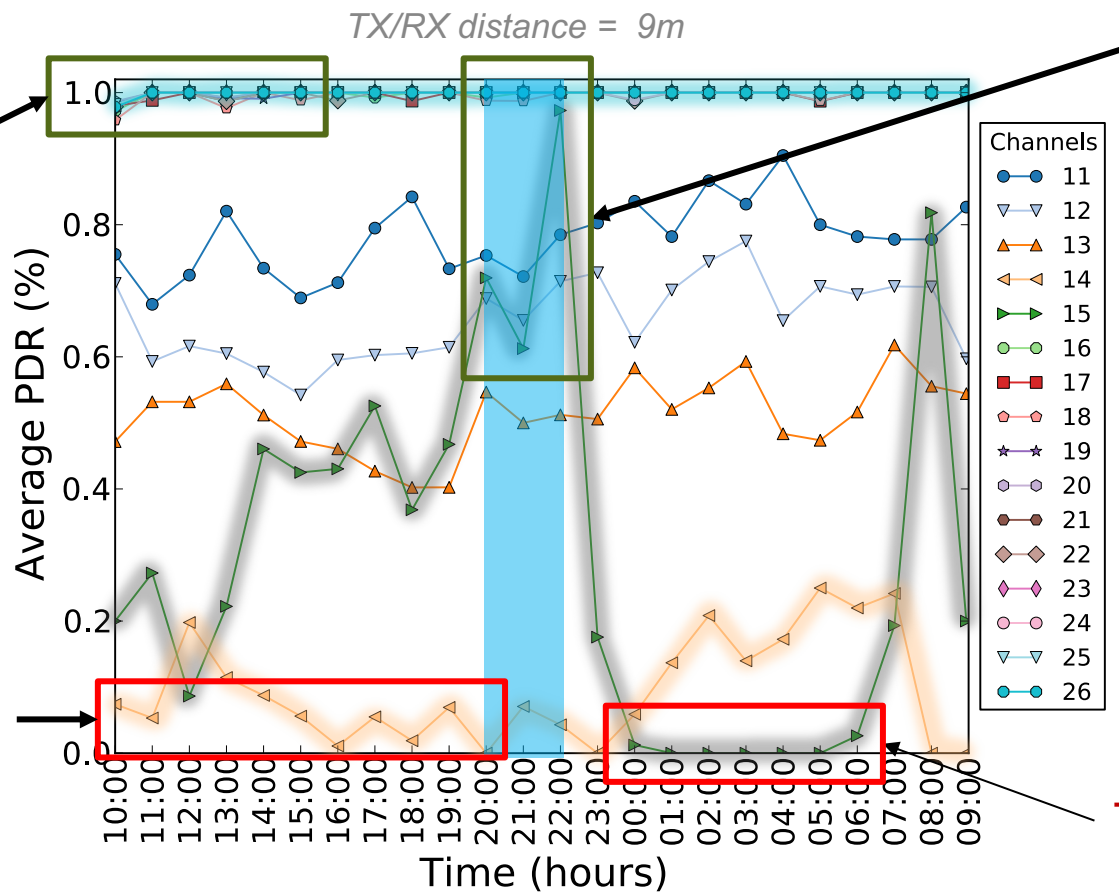

Temporary good: whitelist it (during 2h)

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Variable radio conditions → **dynamic/adaptive blacklisting strategy!**

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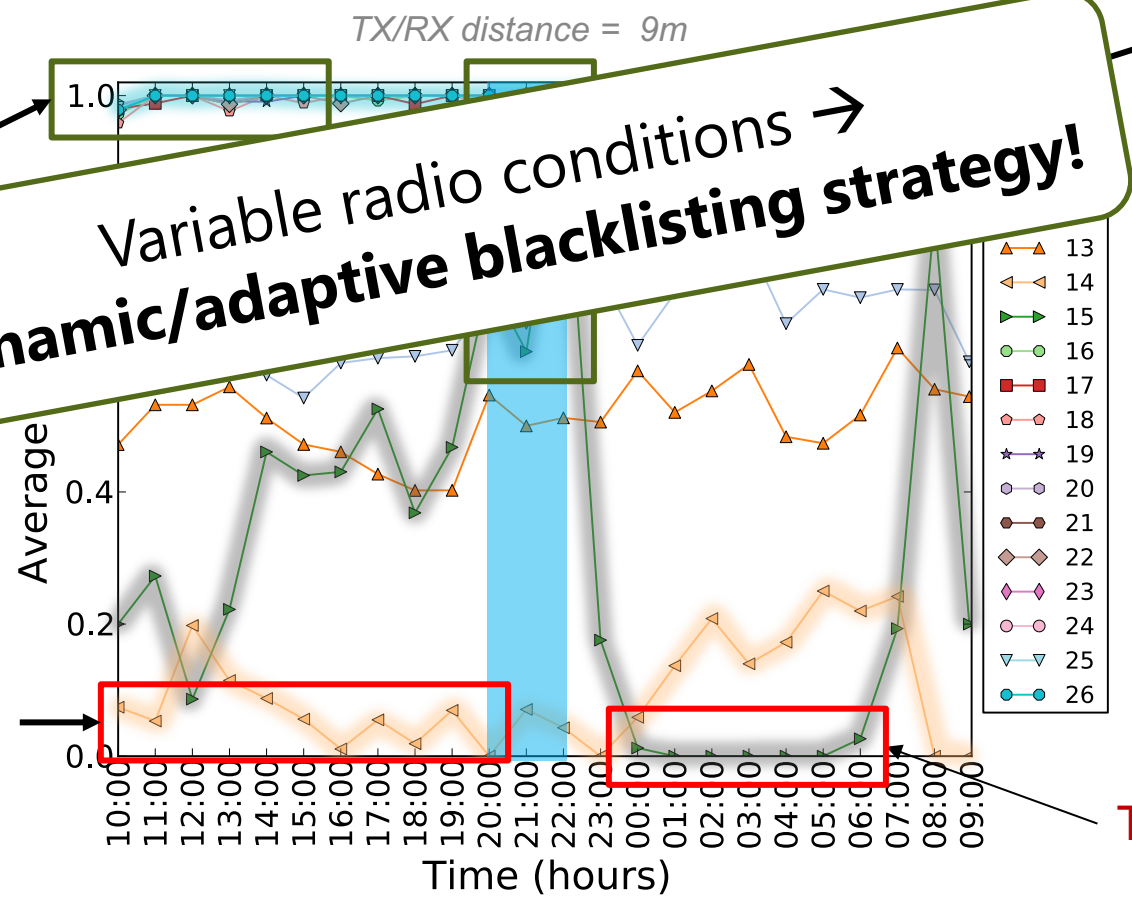

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Blacklisting Techniques

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Distributed Strategy

Link-Based Adaptive Blacklisting Technique

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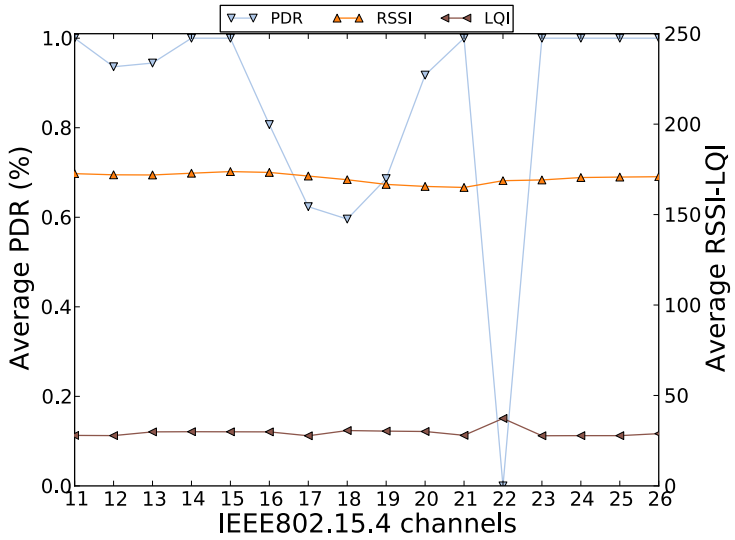
Distributed Strategy

Which Radio Channel Quality Metric Should be Employed?

- Continuously evaluate their radio link qualities, e.g., based on PDR metric.
  - Alternatively, RSSI or LQI: calculated for received data packets.



Distributed Strategy

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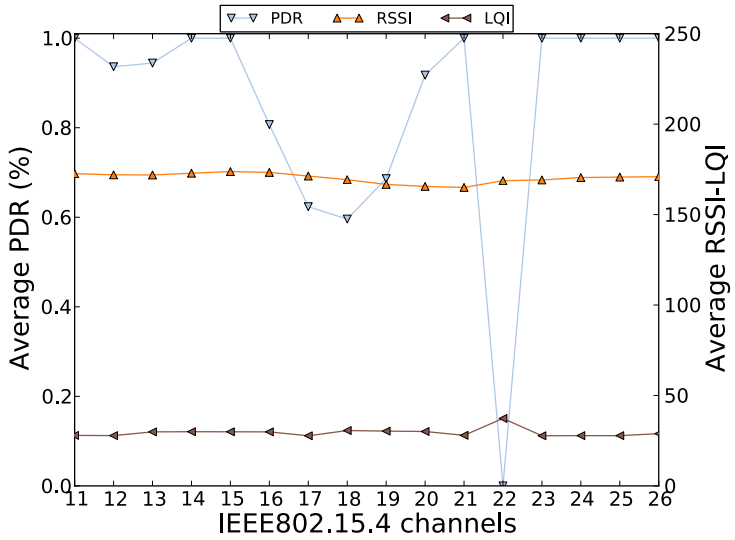
  - Alternatively, RSSI or LQI: calculated for received data packets.
- How to predict the quality of a channel?
  - E.g., Window Mean Exponential Weighted Moving Average (WMEWMA) estimator to smooth the PDR values.

$$PDR_{wmewma}[c] = aPDR_{wmewma}[c] + (1-\alpha)PDR_{last16}[c]$$



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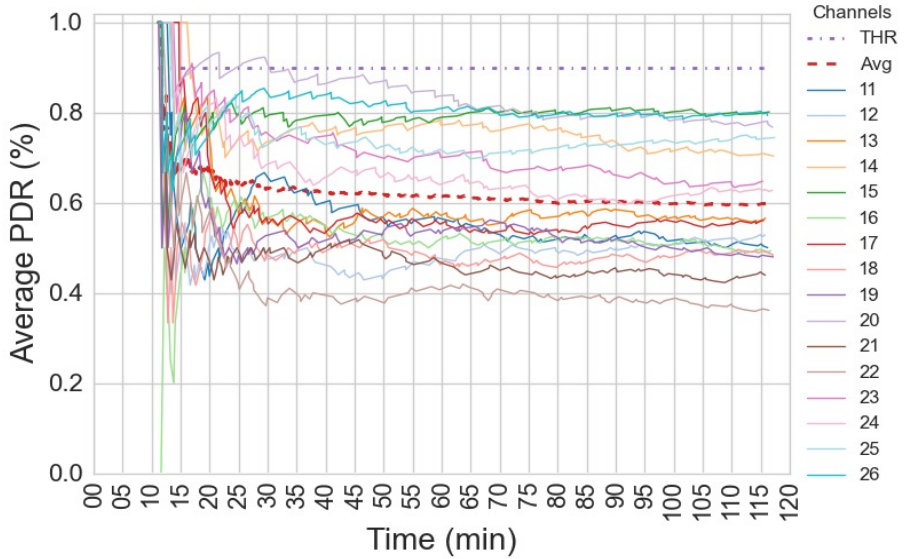

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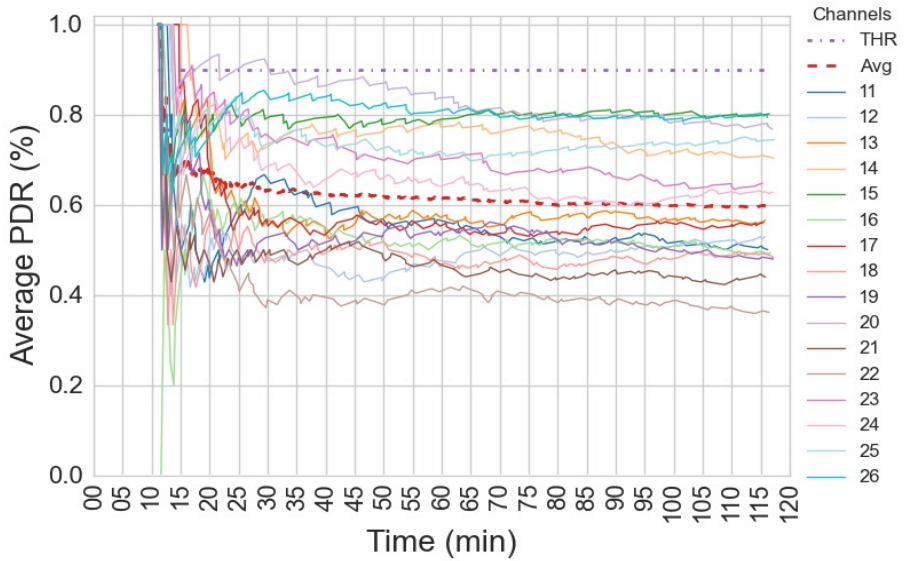
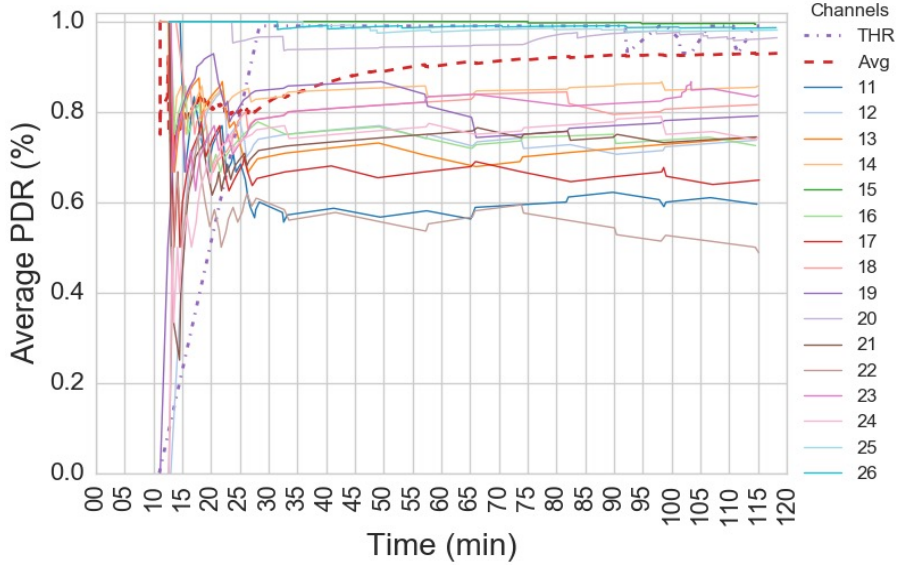
  - Maintains at least **k** radio channels.





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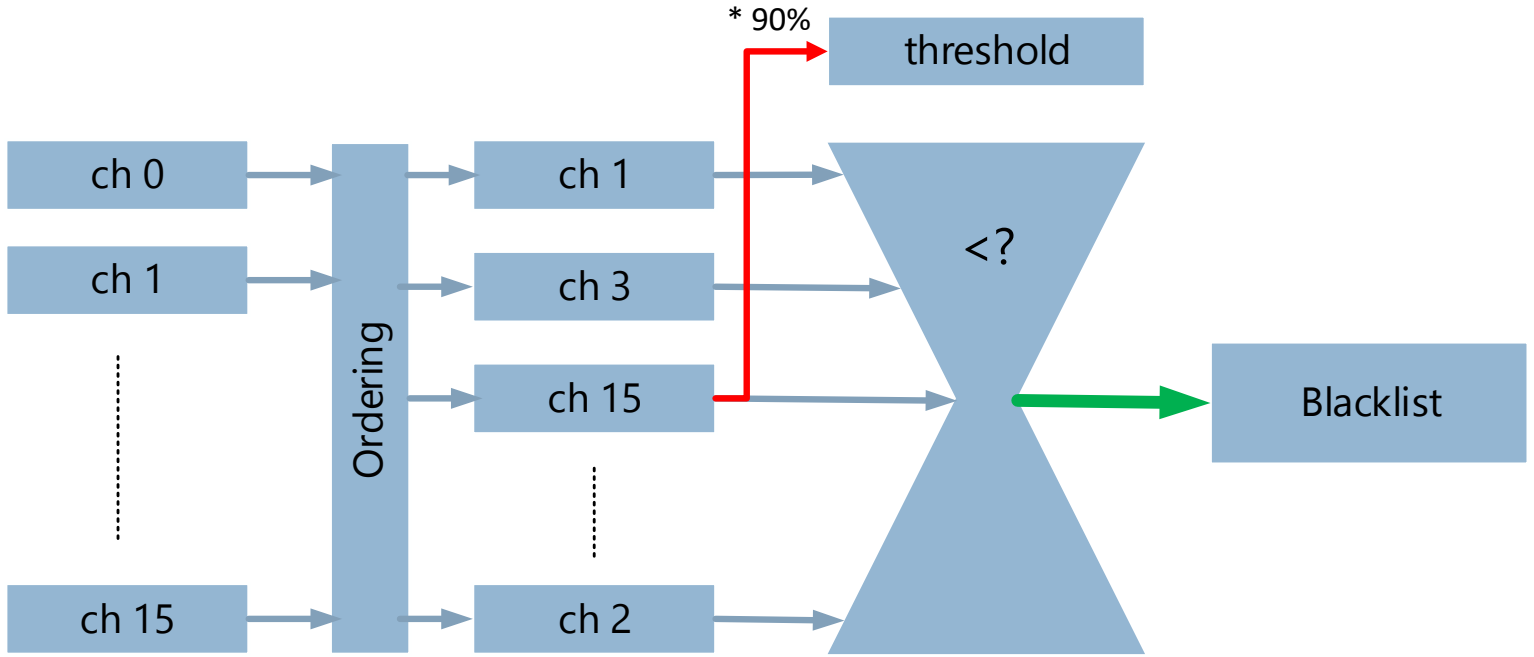
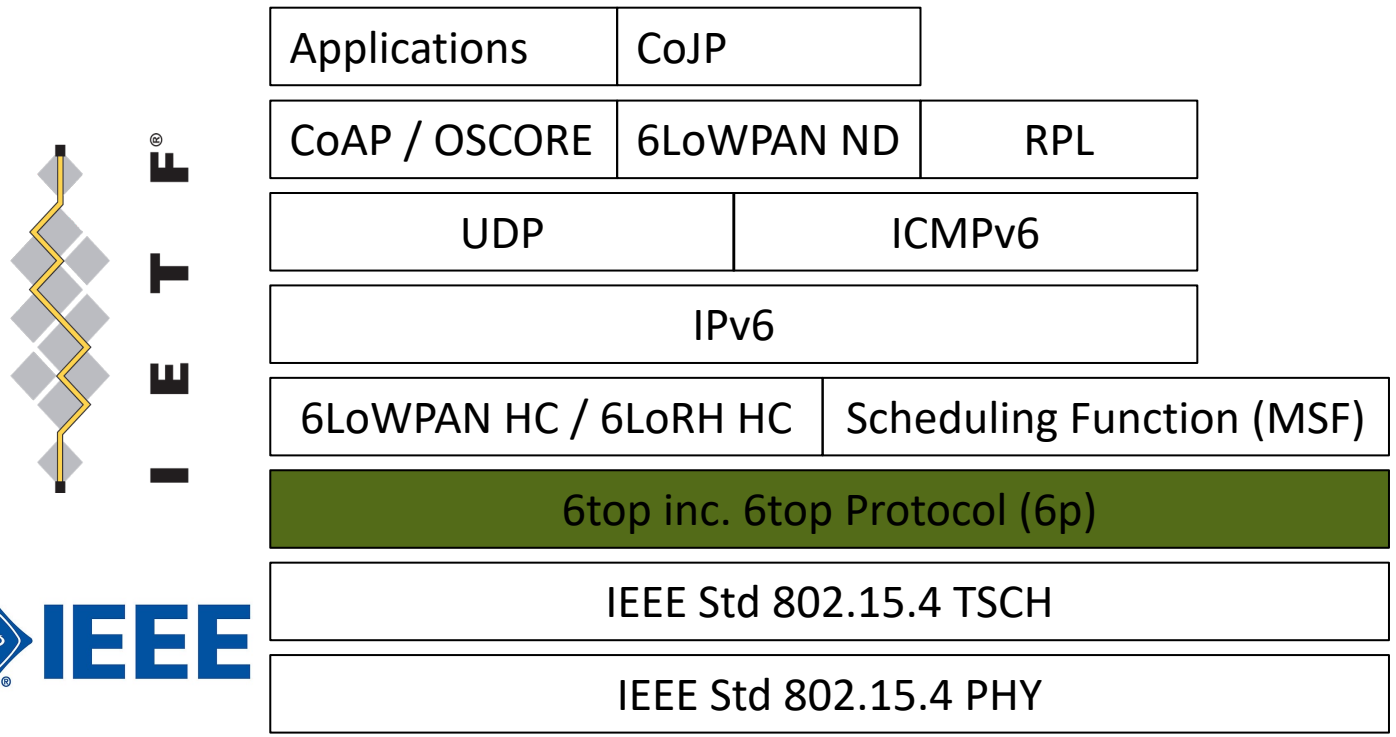
- Blacklist construction depends on the PDR of the k_{th} best radio channel.



Distributed Strategy

6P Control Packets for Whitelist exchanges

- Exchange their ***Whitelists*** (Channel Hopping Sequence → “good radio channels”) through the 6P control packets with their parent nodes.



Distributed Strategy

Modifying the Channel Hopping Sequence

LookUp Table

Index	Channel
0	*16*
1	*17*
2	*23*
3	*18*
4	*26*
5	*15*
6	*25*
7	*22*
8	*19*
9	*11*
10	*12*
11	*13*
12	*24*
13	*14*
14	*20*
15	*21*

ASN	*chOffset*	*k*	*Index*	*Channel*
25	0	0	9	**11**

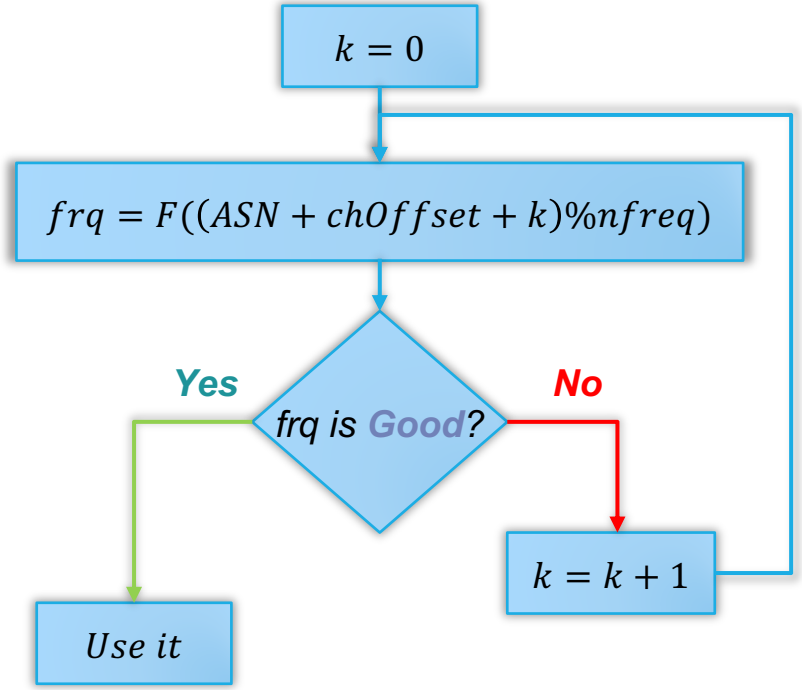
$$(ASN + chOffset + k)\%nfreq$$

$$(25 + 0 + 0)\%16$$

$$9$$

$$F(9)$$

$$11$$



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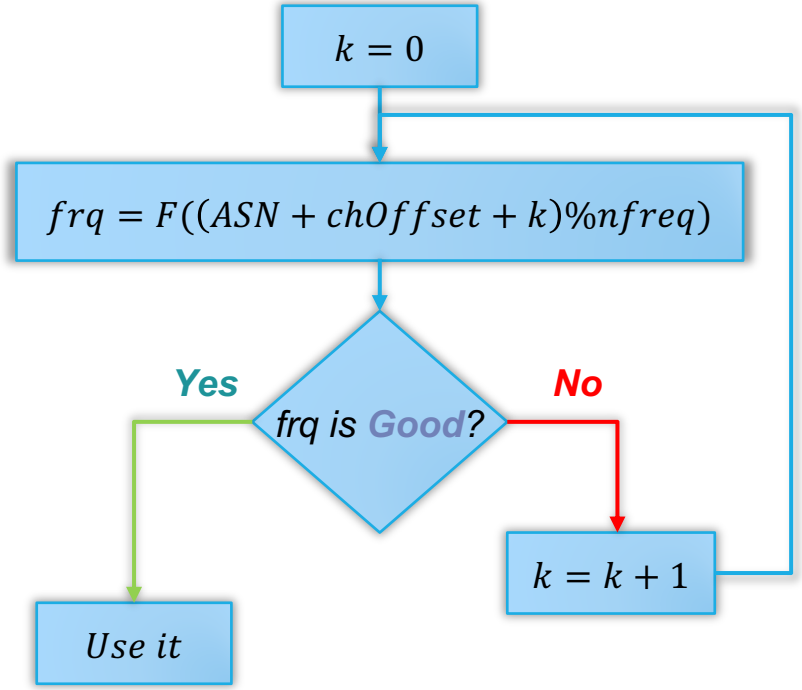
ASN	*chOffset*	*k*	*Index*	*Channel*
25	0	0	9	**11**
33	0	0	1	**17**



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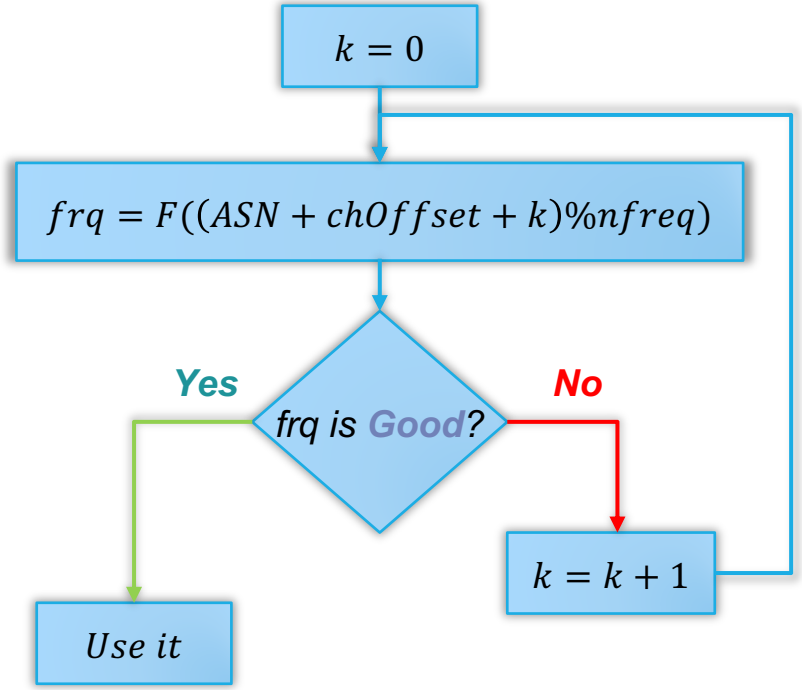
33	0	0	1	**17**
33	0	1	2	**23**



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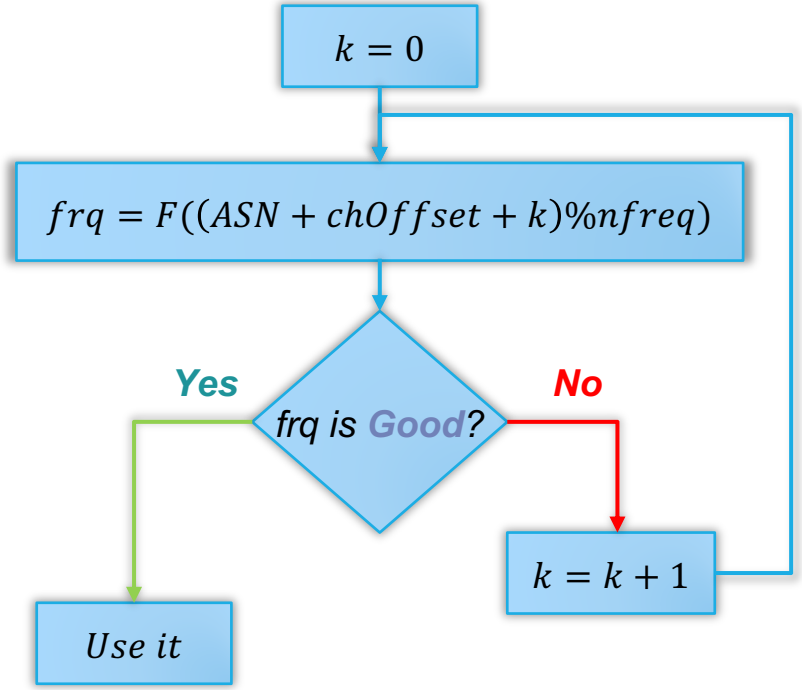


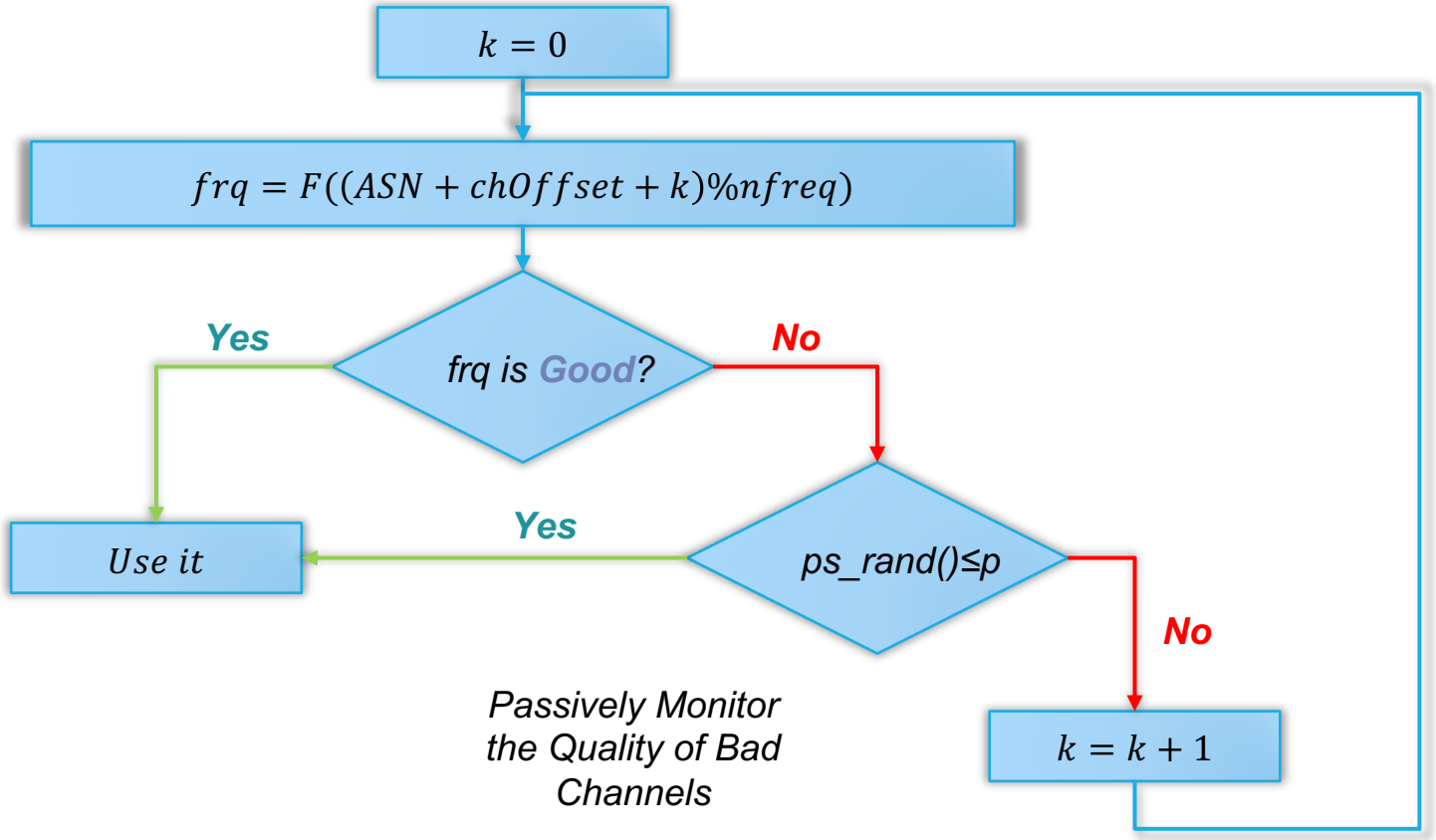
Distributed Strategy

Passively Monitoring the Quality of the Blacklisted Radio Channels

- Probing with control packets:
  - Produces unnecessary traffic.

Approach:

- Good radio channel → let's use it!
- Bad radio hannel:
  - Probability p: let's use the bad channel (monitoring).
  - Probability (1-p): let's use pseudo-randomly a good one.



Internal Collision Issue

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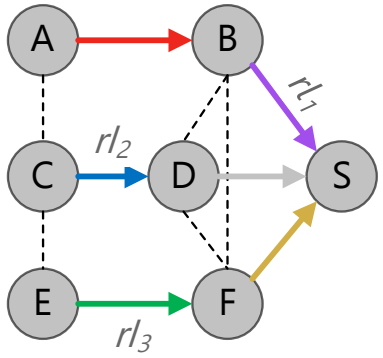
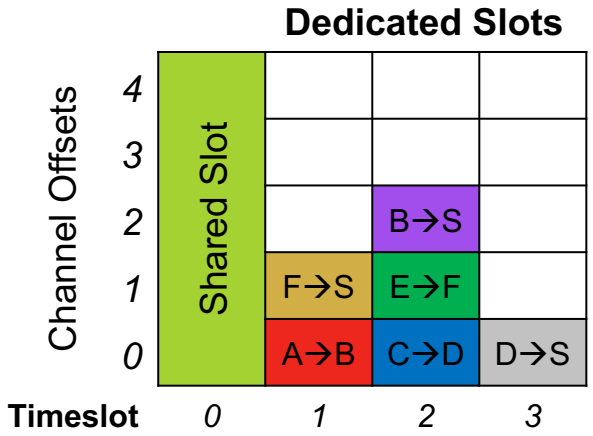
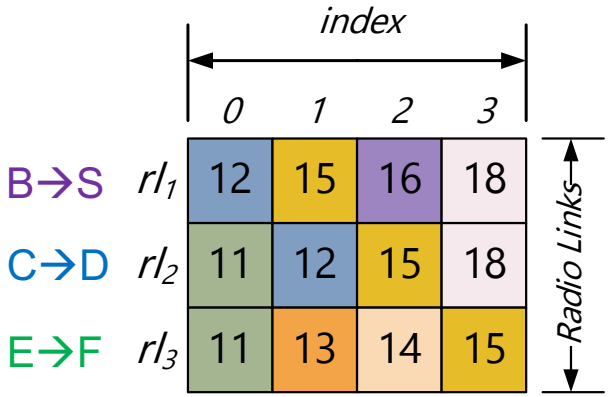
Distributed Strategy
Internal Collision Issue

- However, when two or more radio links are scheduled at the ***same timeslot***, even with ***different channel offsets***, they *may* collide if they ***do not have*** the same ***Channel Hopping Sequence (whitelist)***.





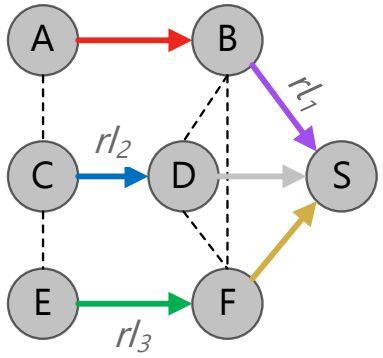


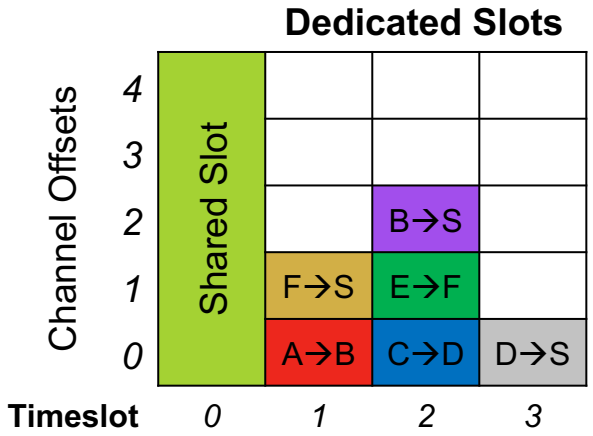
Channel Hopping Sequence

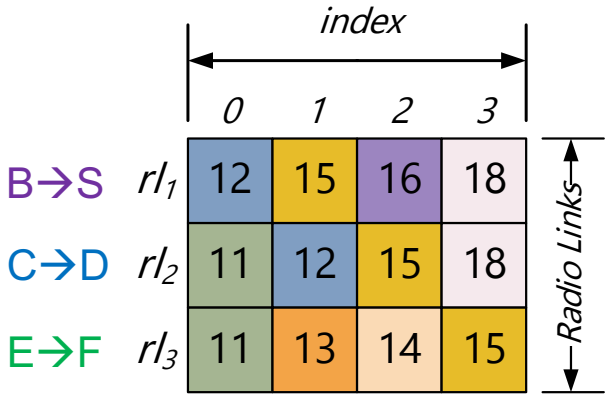
Whitelists

Distributed Strategy
Internal Collision Issue

- However, when two or more radio links are scheduled at the ***same timeslot***, even with ***different channel offsets***, they *may* collide if they ***do not have*** the same ***Channel Hopping Sequence (whitelist)***.







Channel Hopping Sequence

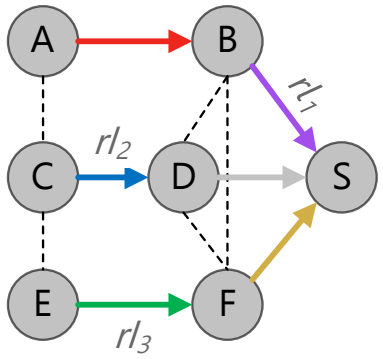
Whitelists

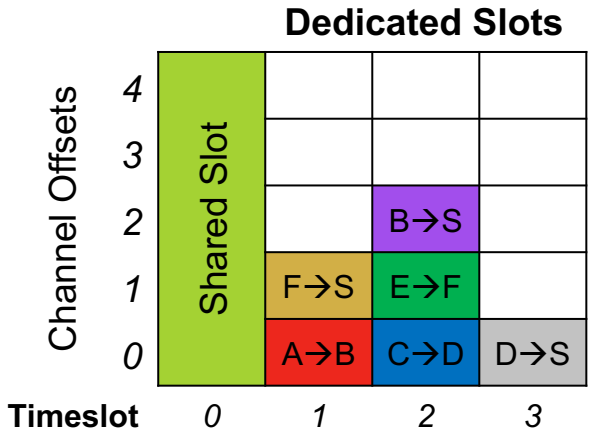
$$Radio\ C. = F[(ASN + chOffset)\%N_{channels}]$$

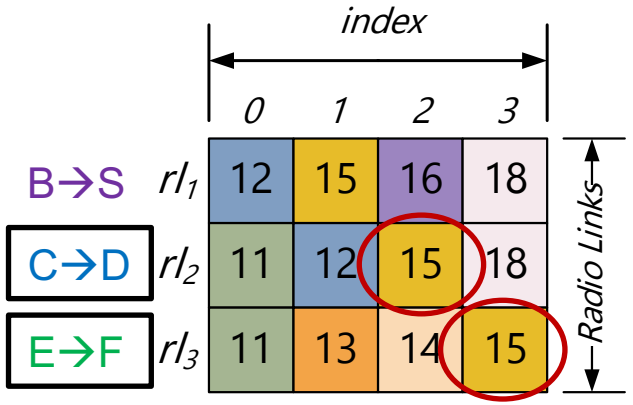
← **index** →

Distributed Strategy
Internal Collision Issue

- However, when two or more radio links are scheduled at the ***same timeslot***, even with ***different channel offsets***, they *may* collide if they ***do not have*** the same ***Channel Hopping Sequence (whitelist)***.







Channel Hopping Sequence

Whitelists

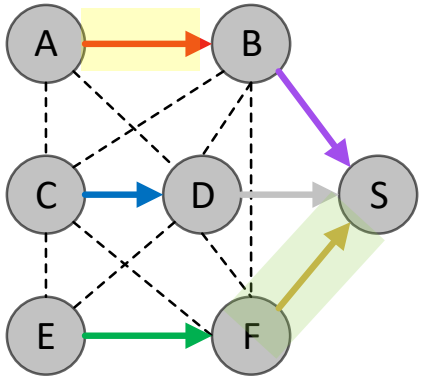
$$Radio\ C. = F[(ASN + chOffset)\%N_{channels}]$$

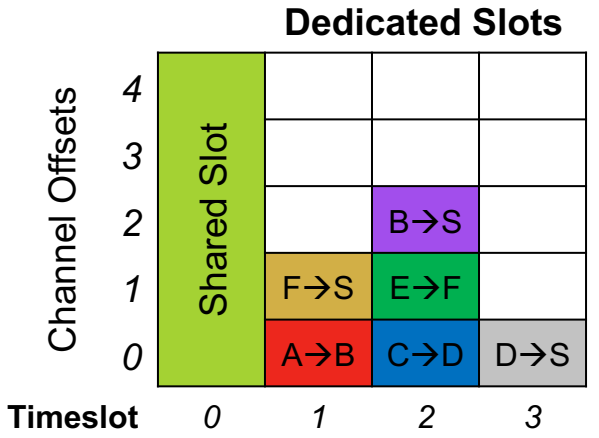
← **index** →

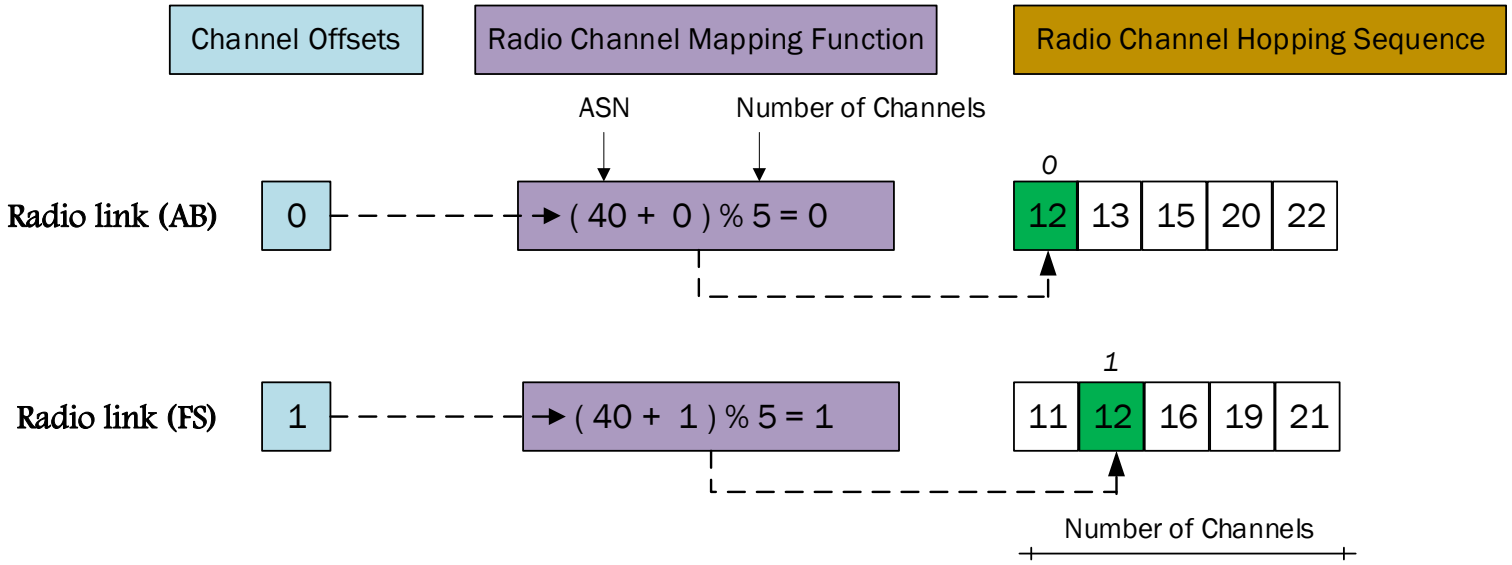
C→D: ASN = 42, COffset = 0 → Radio C = F[(42+0)mod 4] = 2 → 15
E→F: ASN = 42, COffset = 1 → Radio C = F[(42+1)mod 4] = 3 → 15

Distributed Strategy

Internal Collision Issue: Another Example







Travaux Dirigés (TD)

Internal Collision Examples

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Internal Collision Exercises

Exercise 1

	A->B				C->D			
	Channel Offset	2			Channel Offset	1		
	Whitelist	1	5		Whitelist	5	7	
ASN	Radio Channel				Radio Channel			
0								
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								

$$f() = F\{(ASN + Channel\_Offset) \bmod n_{ch}\}$$

Internal Collision Exercises

Exercise 1

	A->B				C->D			
	Channel Offset	2			Channel Offset	1		
	Whitelist	1	5		Whitelist	5	7	
ASN	Radio Channel				Radio Channel			
0	1				7			
1	5				5			**Collision**
2	1				7			
3	5				5			**Collision**
4	1				7			
5	5				5			**Collision**
6	1				7			
7	5				5			**Collision**
8	1				7			
9	5				5			**Collision**
10	1				7			
11	5				5			**Collision**
12	1				7			
13	5				5			**Collision**

$$f() = F\{(ASN + Channel\_Offset) \bmod n_{ch}\}$$

Collision in all even timeslots!

Internal Collision Exercises

Exercise 2

	Links		
	A->B	C->D	E->F
Channel Offset	3	4	2
Whitelist Size	5	5	4
Whitelist	1	2	2
	2	5	7
	6	7	9
	7	9	13
	8	11	

	Links		
ASN	A->B	C->D	E->F
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			

Internal Collision Exercises

Exercise 2

	Links			
	A->B	C->D	E->F	
Channel Offset	3	4	2	
Whitelist Size	5	5	4	
Whitelist	1	2	2	
	2	5	7	
	6	7	9	
	7	9	13	
	8	11		

	Links			
ASN	A->B	C->D	E->F	
0	7	11	9	
1	8	2	13	
2	1	5	2	
3	2	7	7	**Collision**
4	6	9	9	**Collision**
5	7	11	13	
6	8	2	2	**Collision**
7	1	5	7	
8	2	7	9	
9	6	9	13	
10	7	11	2	
11	8	2	7	
12	1	5	9	
13	2	7	13	
14	6	9	2	
15	7	11	7	**Collision**
16	8	2	9	
17	1	5	13	
18	2	7	2	**Collision**
19	6	9	7	
20	7	11	9	
21	8	2	13	
22	1	5	2	
23	2	7	7	**Collision**
24	6	9	9	**Collision**
25	7	11	13	
26	8	2	2	**Collision**

Internal Collision Exercises

Exercise 2 with Schedule

	Links										Links			
	A->B	C->D	E->F		Slotframe Length	11		ASN	Slot	Transmit	A->B	C->D	E->F	
Channel Offset	3	4	2		Schedule			0	0	#N/A				
Whitelist Size	5	5	4		TX slots	3		1	1	#N/A				
Whitelist	1	2	2			6		2	2	#N/A				
	2	5	7			7		3	3	1	2	7	7	Collision
	6	7	9					4	4	#N/A				
	7	9	13		Number of Collisions	9		5	5	#N/A				
	8	11			Number of TX	35		6	6	1	8	2	2	Collision
					%	25.71%		7	7	1	1	5	7	
								8	8	#N/A				
								9	9	#N/A				
								10	10	#N/A				
								11	0	#N/A				
								12	1	#N/A				
								13	2	#N/A				
								14	3	1	6	9	2	
								15	4	#N/A				
								16	5	#N/A				
								17	6	1	1	5	13	
								18	7	1	2	7	2	Collision

Hybrid Strategy

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Hybrid Strategy

Multiple Channel Offsets Assignment per Timeslot

- Hybrid Strategy:
  - Adaptive multiple channels offsets assignment on a ***Timeslot basis***.

Hybrid Strategy
Multiple Channel Offsets Assignment per Timeslot

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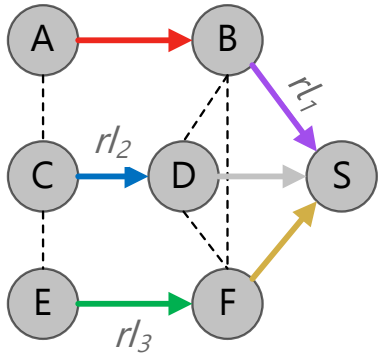
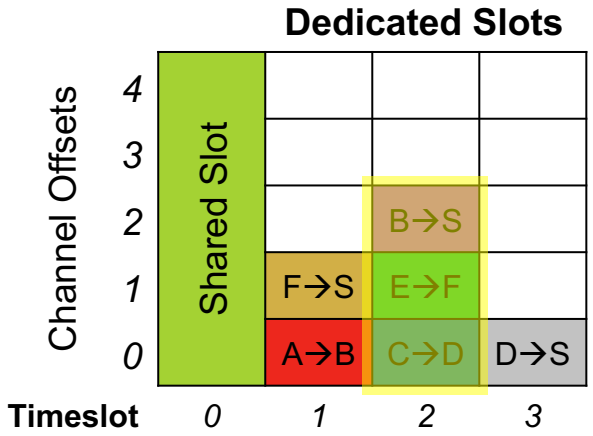
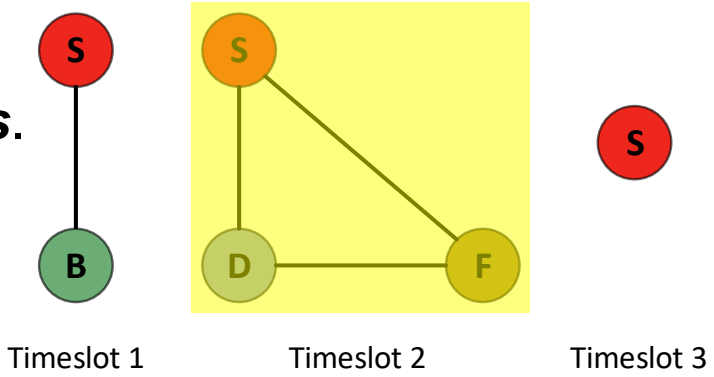


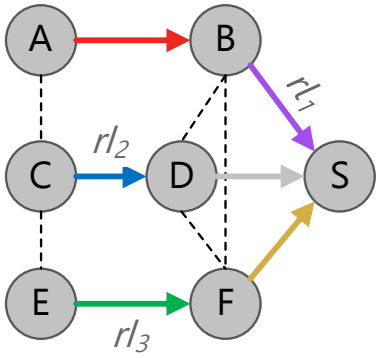


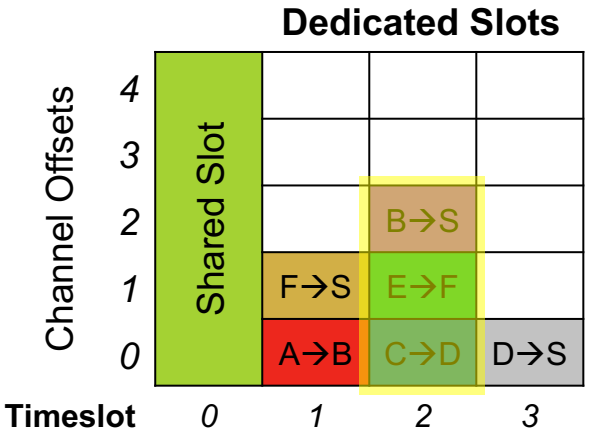
Hybrid Strategy

Interference Graph of Radio Links Scheduled in the same Timeslot

- Hybrid Strategy:
  - Adaptive multiple channels offsets assignment on a ***Timeslot basis***.
  - Construct an interference graph of the radio links scheduled in the same timeslot.



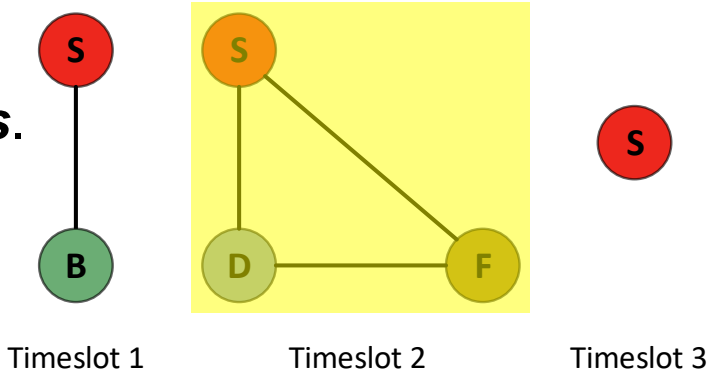


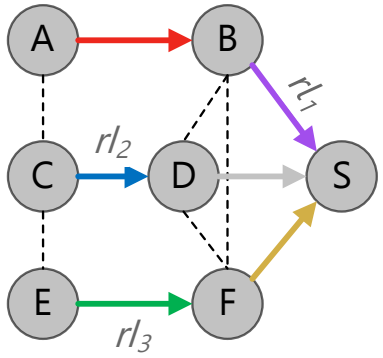


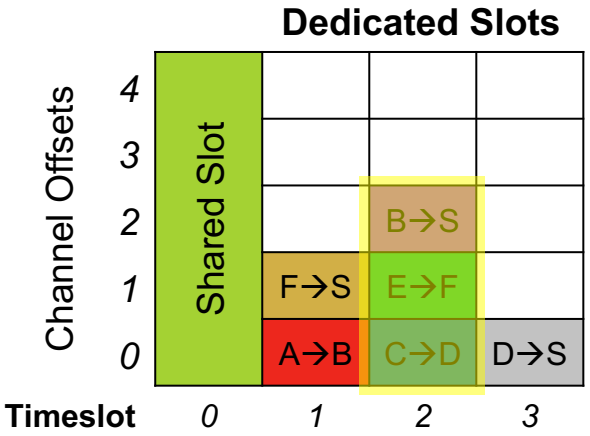
Hybrid Strategy

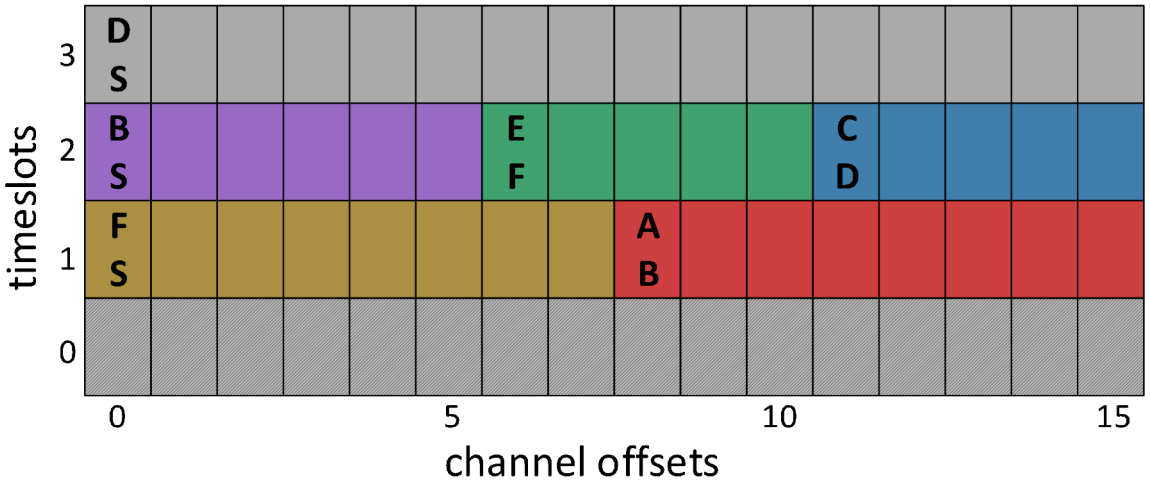
Assign Multiple Channel Offsets per Radio Link

- Hybrid Strategy:
  - Adaptive multiple channels offsets assignment on a ***Timeslot basis***.
  - Construct an interference graph of the radio links scheduled in the same timeslot.
  - Assigns multiple channel offsets on each radio link.









$$Radio\ C. = F[(ASN + chOffset)\%N_{channels}]$$

← **index** →

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Hybrid Strategy

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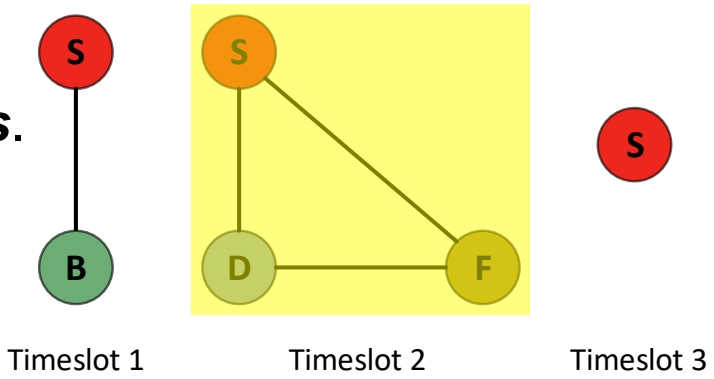

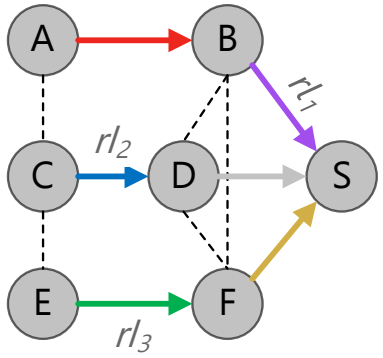

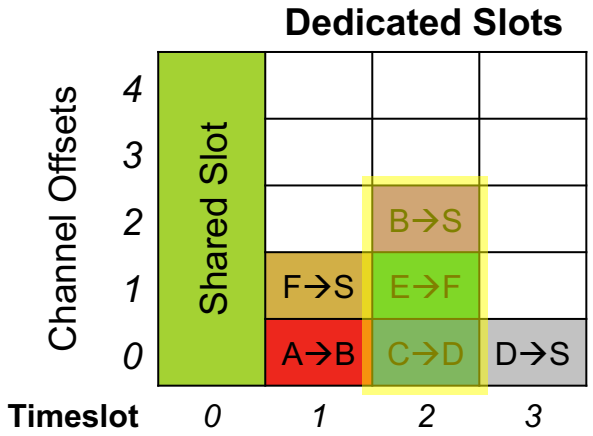

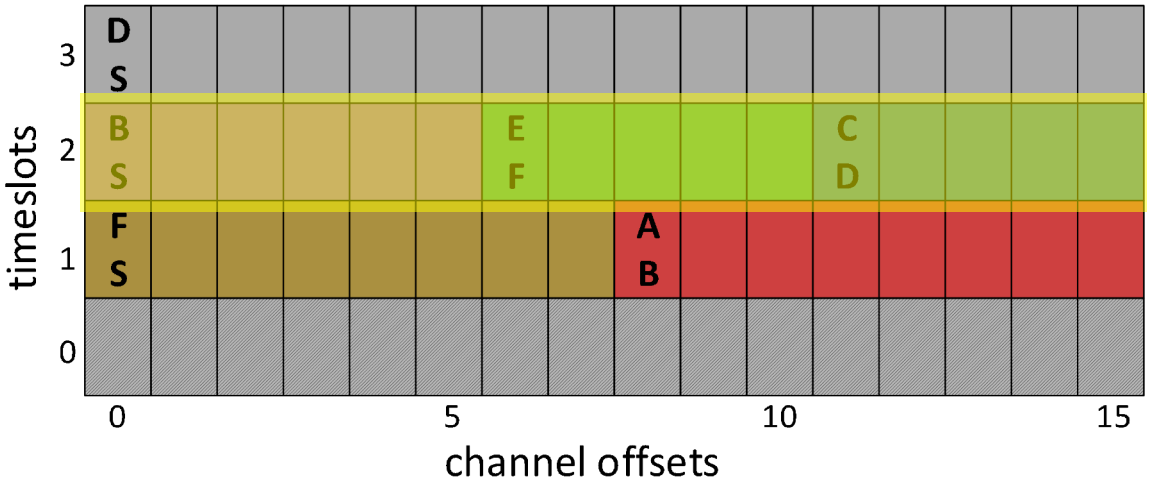

$$Radio\ C. = F[(ASN + chOffset)\%N_{channels}]$$

← **index** →

Hybrid Strategy
Example

- Hybrid Strategy:
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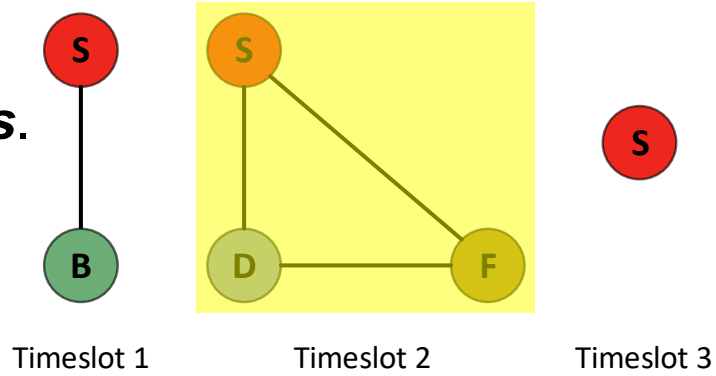
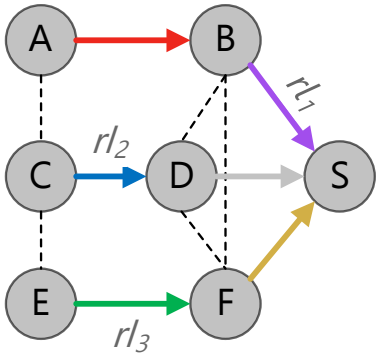
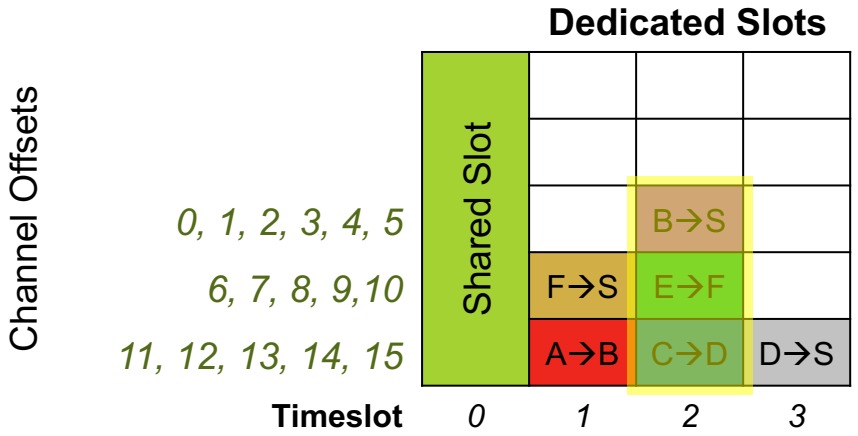
  - Construct an interference graph of the radio links scheduled in the same timeslot.
  - Assigns multiple channel offsets on each radio link.





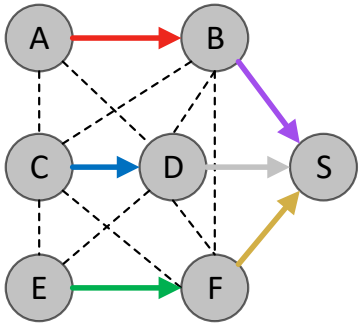


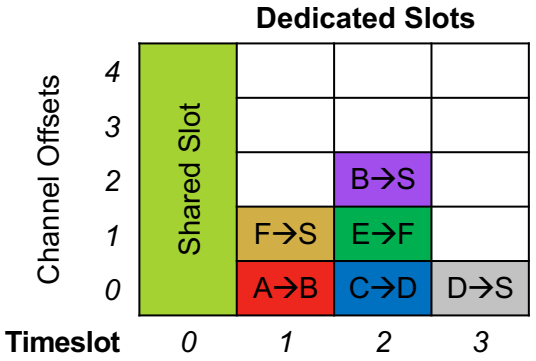
$$Radio\ C. = F[(ASN + chOffset)\%N_{channels}]$$

← **index** →

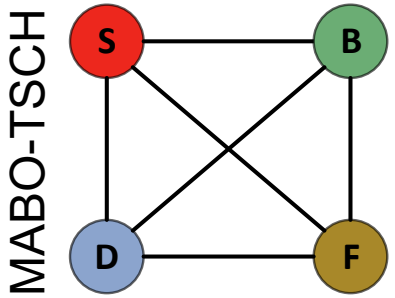
Hybrid Strategy

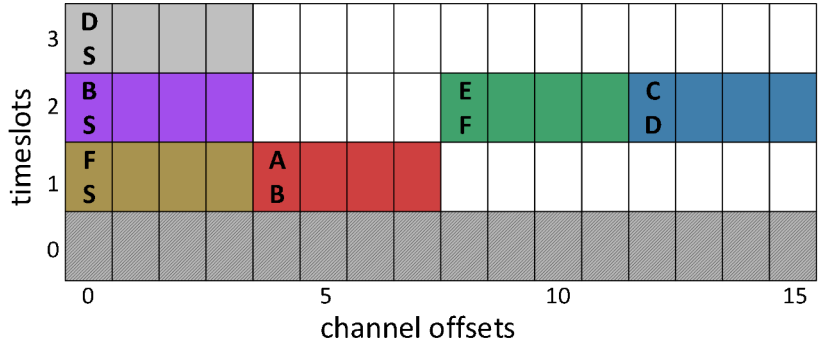
Receiver-based vs Timeslot-based Multiple Channel Offset Assigment



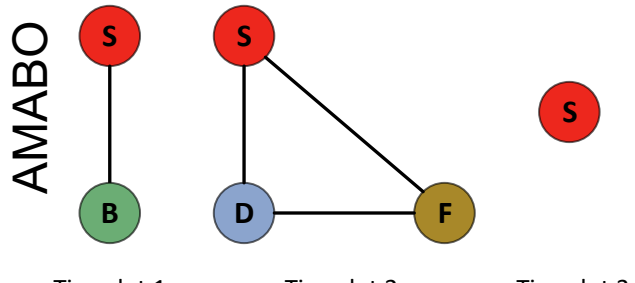


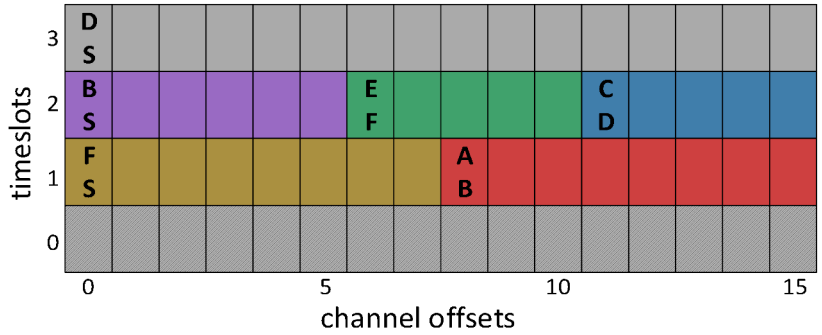
AVG 4 Channel Offsets per Transmission





AVG 8 Channel Offsets per Transmission





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Centralized Strategy

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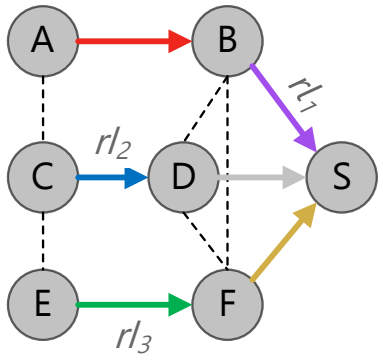
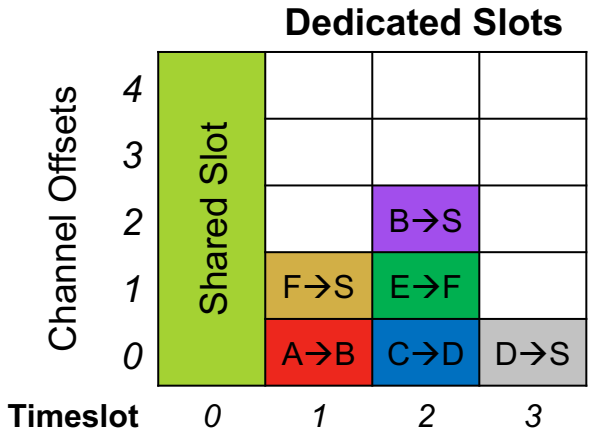
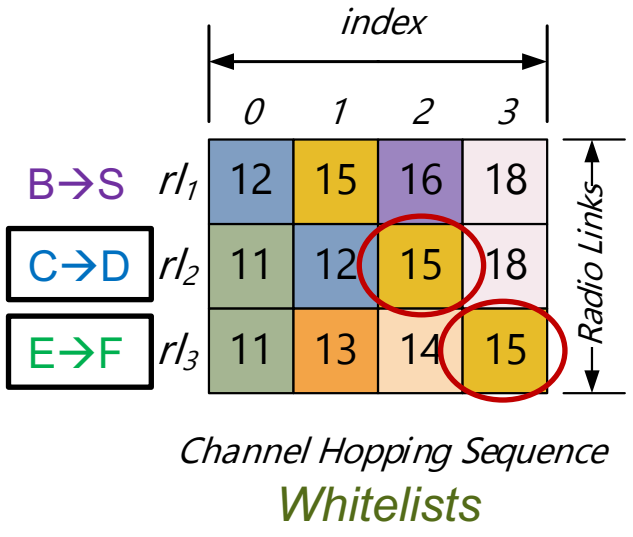
Blacklisting Techniques
Centralized Strategy

- Centralized Strategy:
  - Greedy Re-Ordering Process.
  - Adapt the whitelists for each radio link by re-arranging the Channel Hopping Sequence (the conflicting whitelists).
  - The **same radio channels** to be allocated on the **same column** (index)**.**

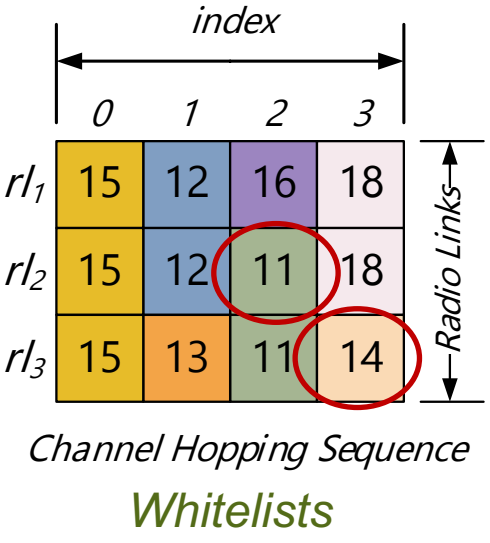






Channel Hopping Sequence

Whitelists



Channel Hopping Sequence

Whitelists

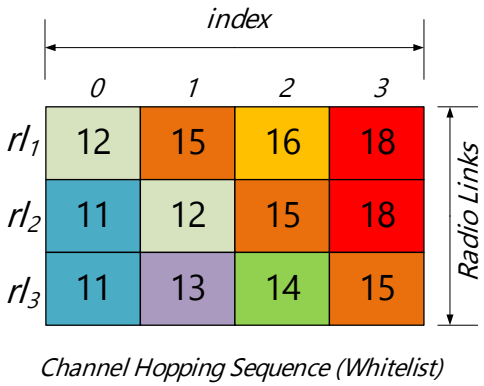
$$Radio\ C. = F[(ASN + chOffset)\%N_{channels}]$$

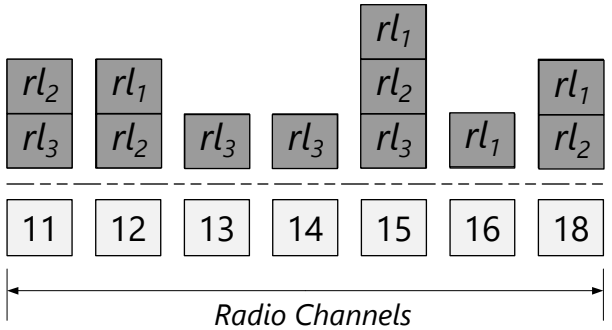
← **index** →

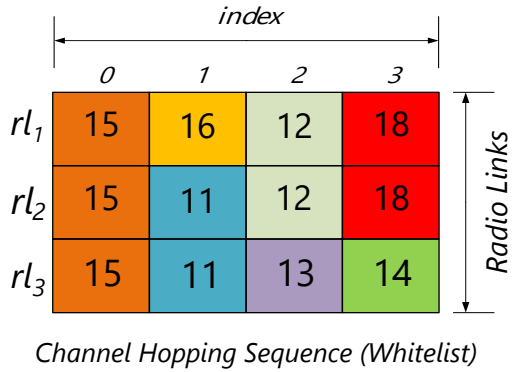
C→D: ASN = 42, COffset = 0 → Radio C = F[(42+0)mod 4] = 2 → 11
E→F: ASN = 42, COffset = 1 → Radio C = F[(42+1)mod 4] = 3 → 14

Greedy Re-Ordering Process

- We first construct the list of links associated with each radio channel
- Each of the columns in the matrix is complemented by the channels that fill the maximum number of its empty cells.







Performance Evaluations

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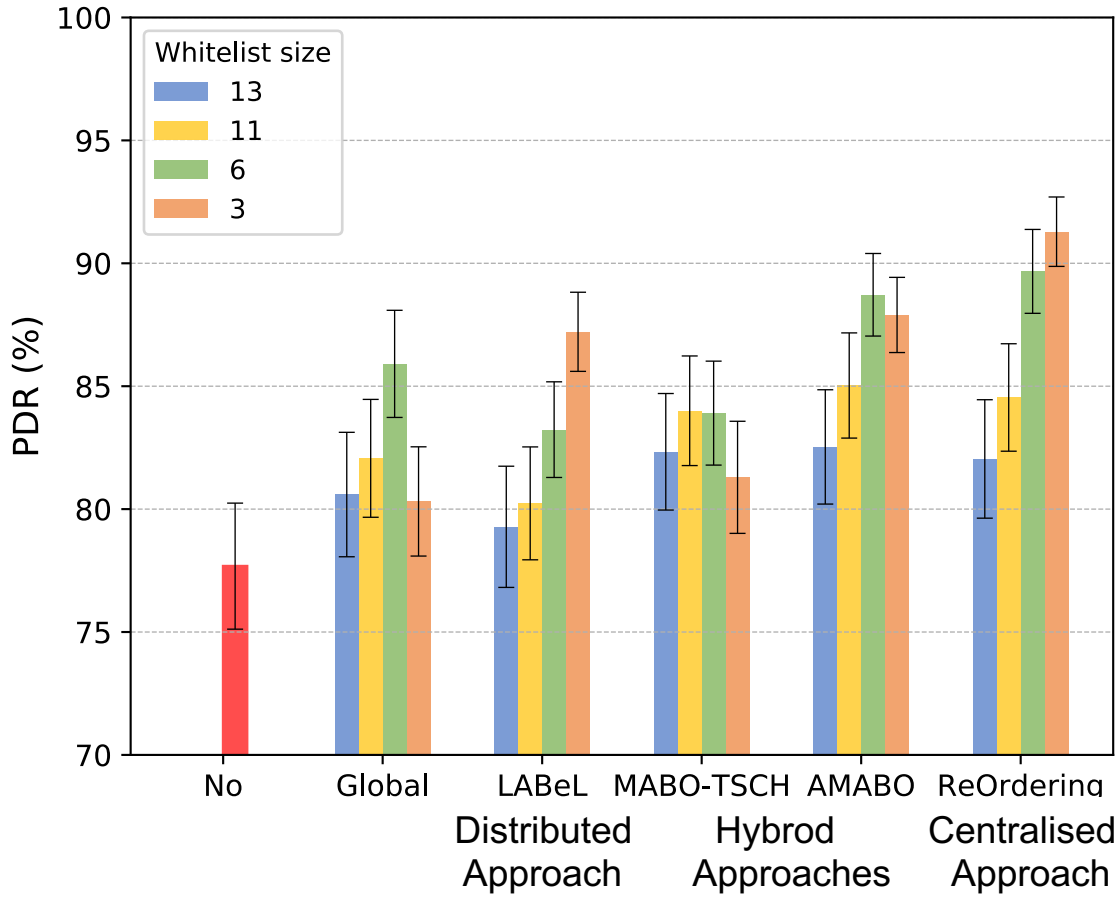
Performance Evaluation

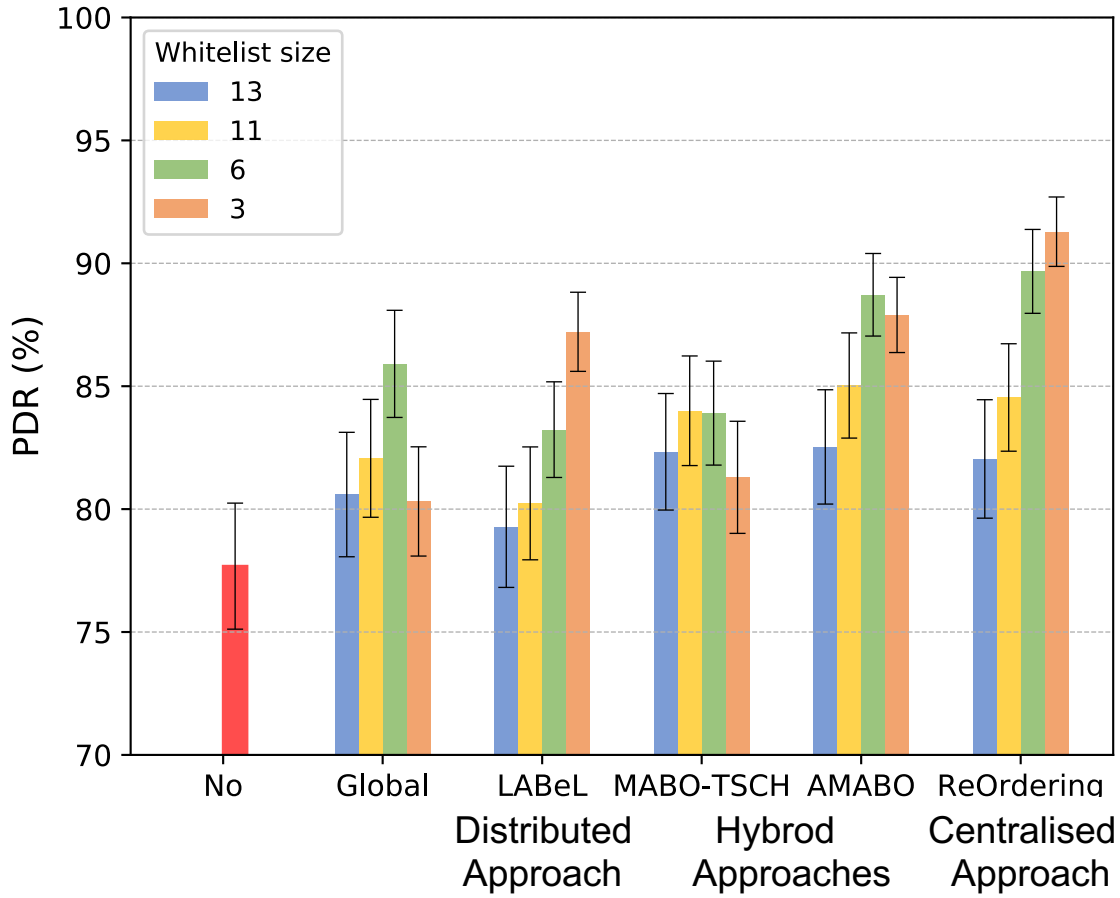
Link-level Packet Delivery Ratio



Performance Evaluation

Link-level Packet Delivery Ratio

- **No Blacklisting** Strategy (default TSCH): worst performance.
- **Global**: some of the whitelisted radio channels provide a lower PDR for some links.



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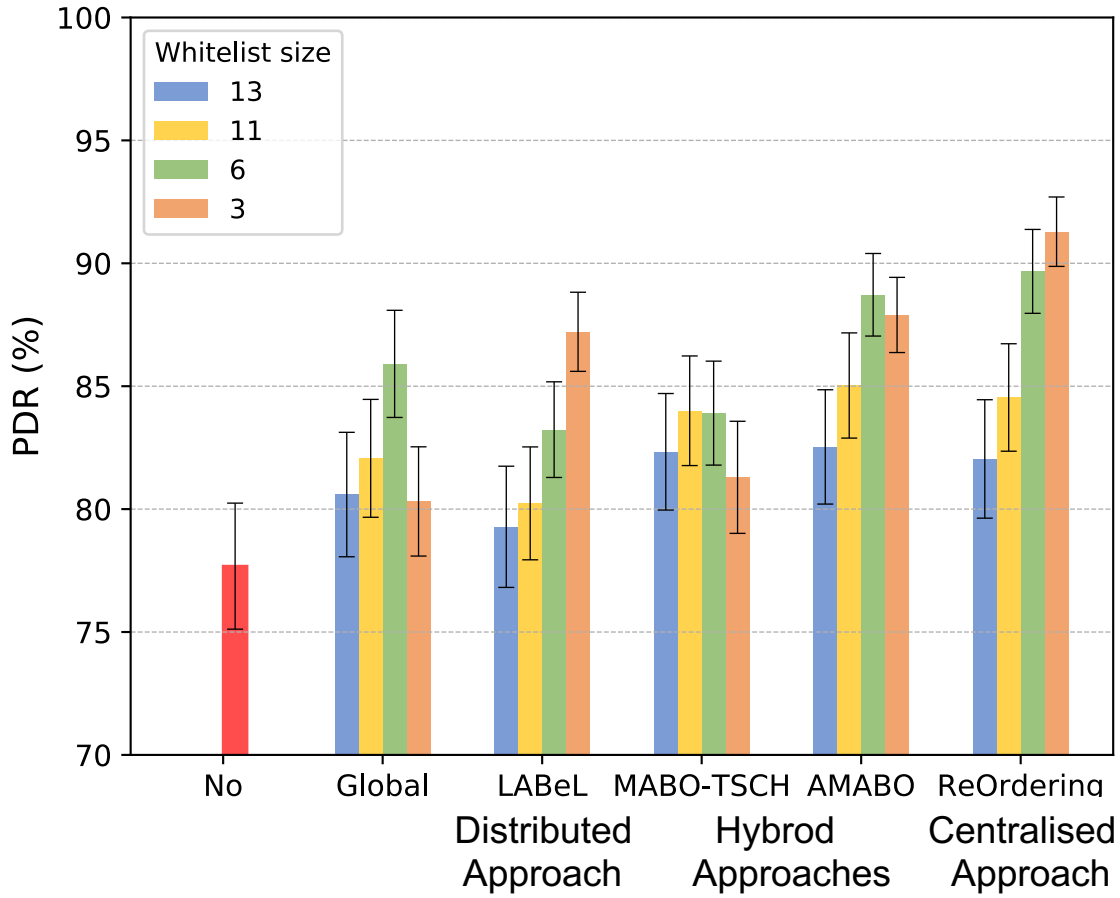

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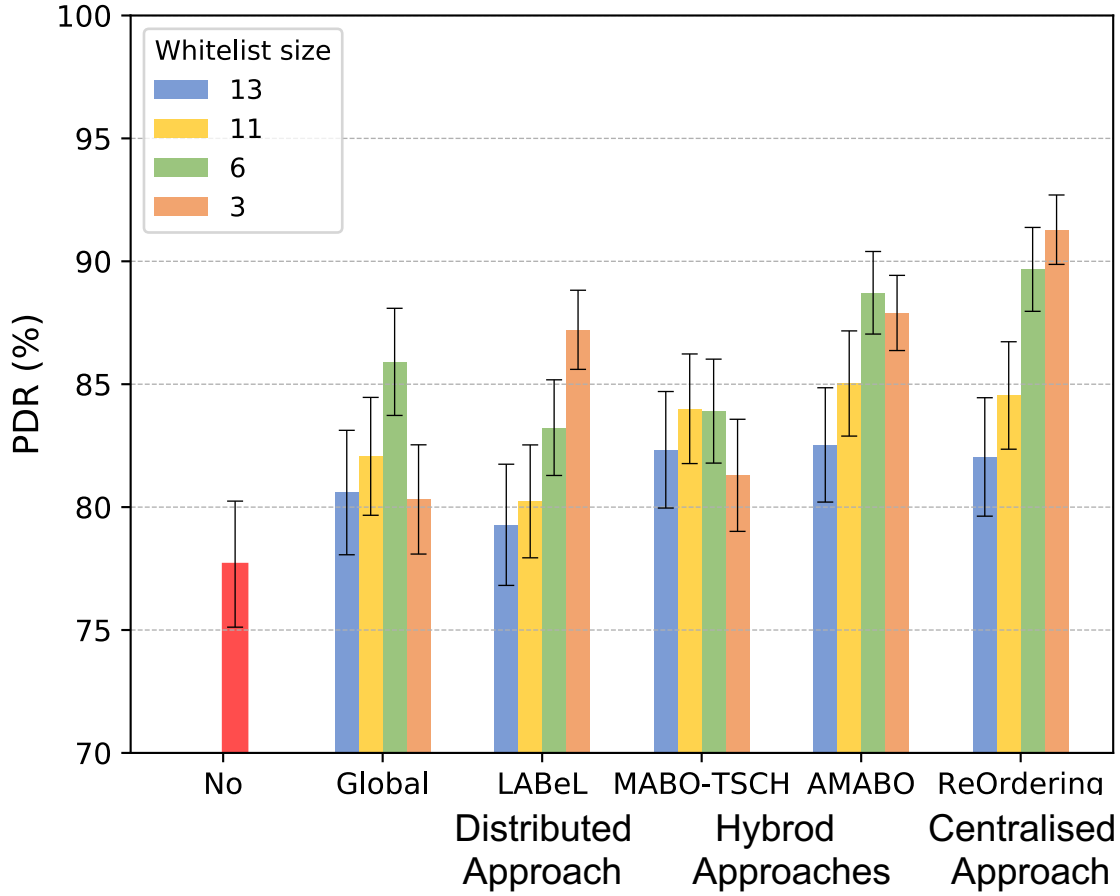

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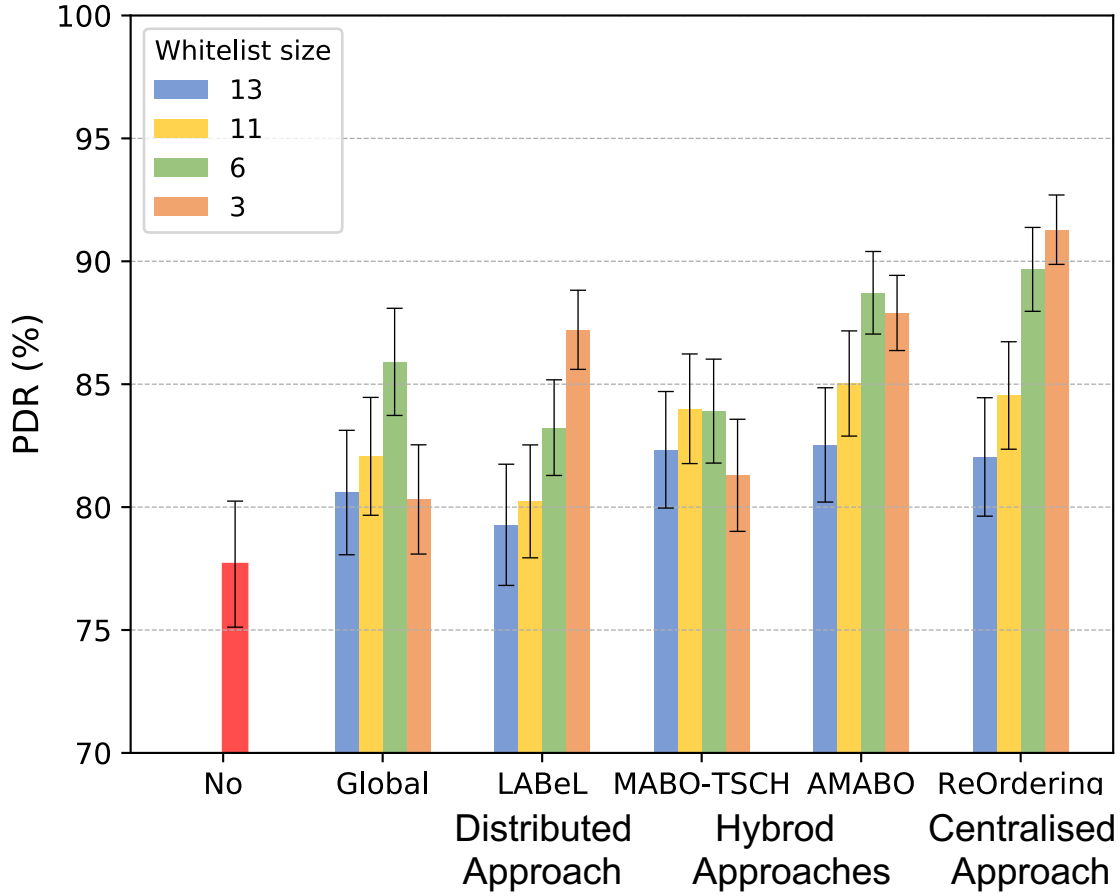
- **Hybrid**: presents better performance than LABeL in scenarios with small size of blacklists, since LABeL introduces internal collisions.
- **Centralized** (Re-Ordering): best performance, links use only their best radio channels.
  - However, slow converging/adaptation time to link quality variations.



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Medium Access Control (MAC)

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