
BWP-Aware Real-Time Scheduling for Heterogeneous UEs in Industrial 5G Systems

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Real-time means meeting every deadline

Correct data

+

Correct timing

Every packet must finish before its application deadline.



Autonomous Driving

Source: KVUE

Timing failure
unacceptable!



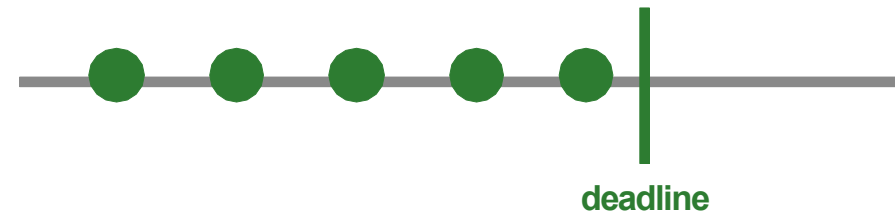
Industrial Automation

Source: ABB

Low average latency



Real-time guarantee



Low average latency does not guarantee
real-time behavior.

Heterogeneous UEs in industrial systems

Application	5G device	UE capability	Traffic specifications
Wired-to-wireless replacement	Industrial 5G gateway	100 MHz Full NR	1-30 ms 1.5 KB, 2-5 UEs
AGV control	Ericsson Cradlepoint	60 MHz Mid NR	10-100 ms 1 KB, 5-10 UEs
TSN-based C2C	Siemens SCALANCE	60 MHz Mid NR	4-8 ms 40 B, 5-10 UEs
Motion control	Bosch Rexroth IndraDrive Mi	20 MHz RedCap	0.5-2 ms 50 B, <=20 UEs

One cell, three capability tiers

100 MHz bandwidth

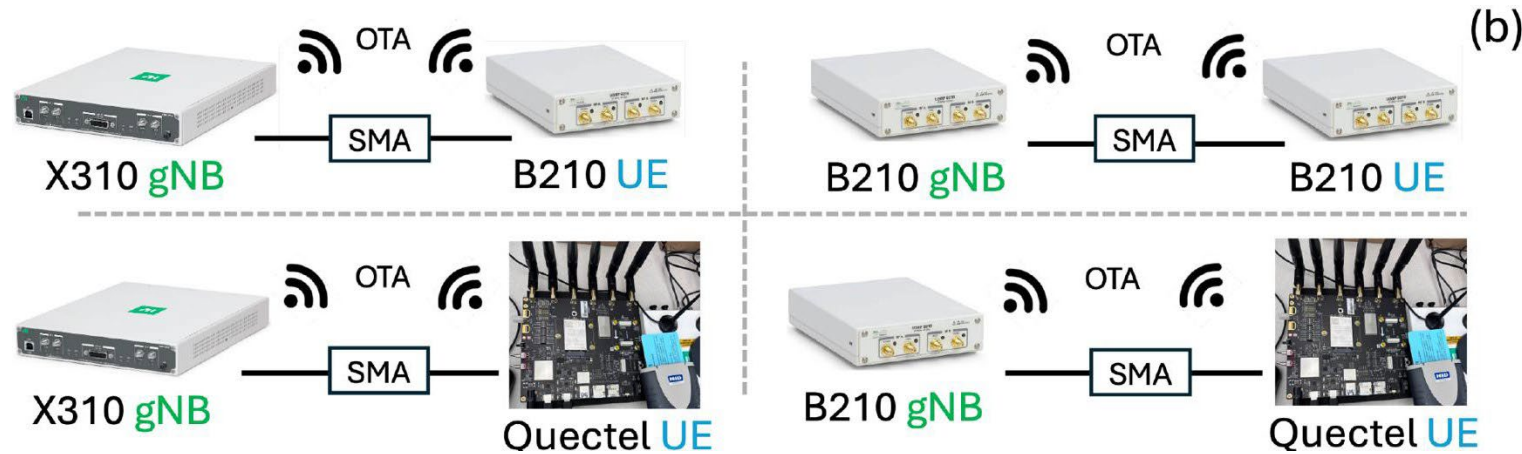
Full NR 100 MHz

Mid NR 60 MHz

20 RedCap 20 MHz

How can heterogeneous industrial UEs share a wideband network while every real-time flow still meets its deadline?

OAI testbed isolates UE capability



Device limits

X310	160 MHz
B210	56 MHz
Quectel	100 MHz

Controlled single-UE scenarios

Carrier and BWP: 20–80 MHz
Link: OTA or attenuated SMA

Questions

- H1 Can capability block attachment?
- H2 Can a smaller BWP restore it?
- H3 Does BWP size cap usable RBs?

BWP validation

1

H1 80 MHz carrier

The 56 MHz B210 cannot attach.

2

H2 40 MHz BWP

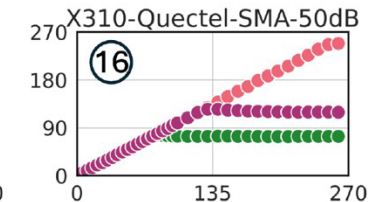
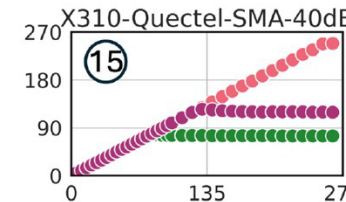
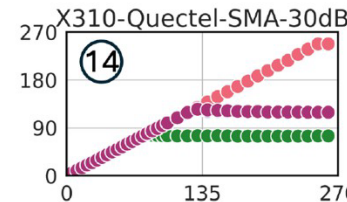
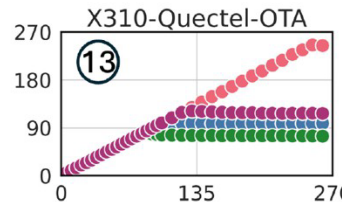
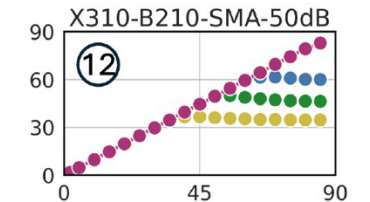
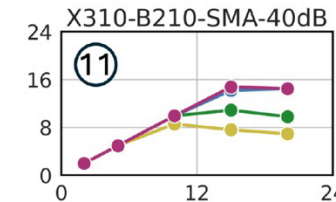
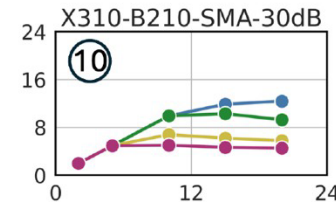
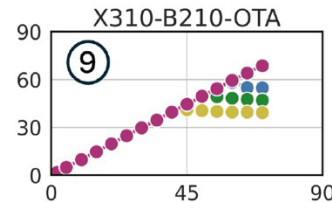
The same B210 attaches on the 80 MHz carrier.

3

H3 Configured BWP

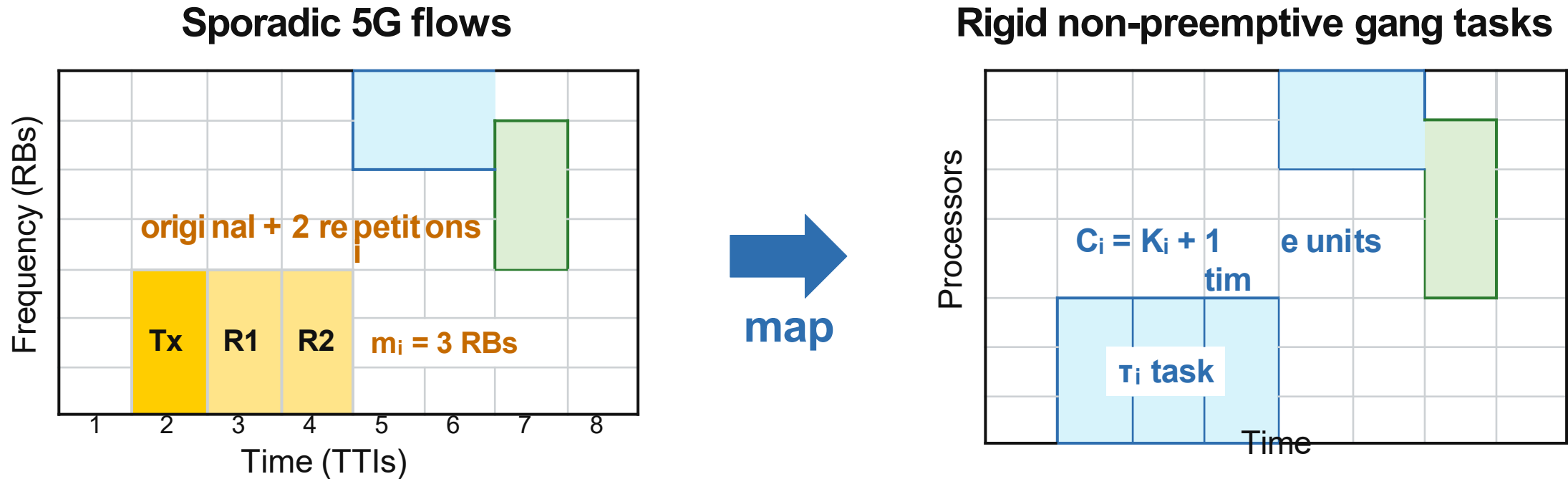
Throughput stops growing at the BWP boundary.

X310 gNB measurements



BWP controls admission and the RBs available to each UE.

System model: 5G flows map to gang tasks



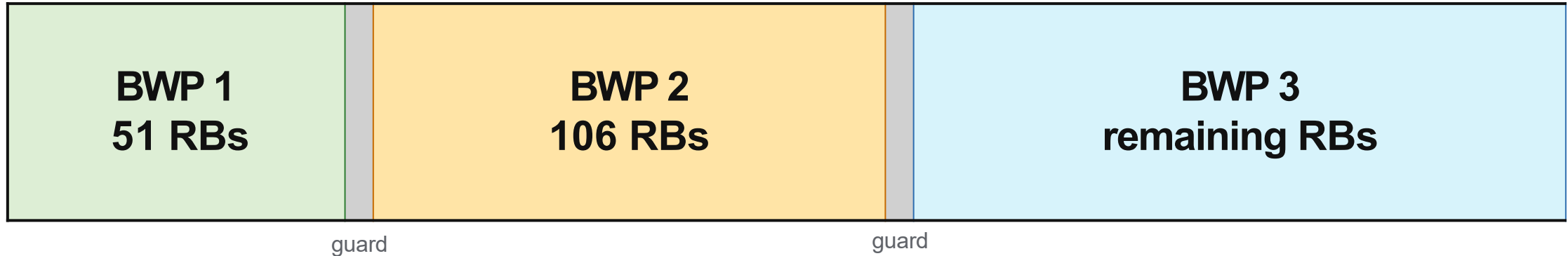
Flow model: $f_i = \langle T_i, D_i, C_i, m_i, B_i \rangle \mid \langle \text{Period, deadline, trans time, RB demand, max BWP} \rangle$

Problem statement

Partition the carrier into BWPs; Allocate each UE to one BWP; All deadlines are met

A BWP is an NP-FP gang task system

100 MHz carrier



Within each BWP

- RBs act as processors.
- Each flow requires m_i RBs together.
- Each packet executes for C_i TTIs without preemption.
- Fixed priority determines which ready gang starts.

Configuration feasibility

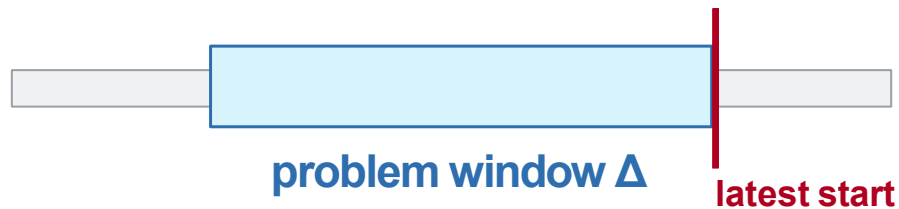
- 1 Every flow passes the NP-FP gang schedulability test inside its BWP.
- 2 $|\rho(u_i)| \leq B_i$ for every UE.
- 3 $\sum |\rho_j| + (|B| - 1)G \leq B$.

Analytical core: certify every flow set sharing a BWP

Fixed: the SOTA NP-FP gang schedulability test

High-level idea

For the job J_k under analysis, Fixed constructs a problem window Δ in which enough processors must stay occupied to prevent J_k from starting before its deadline.



If the total interference bound is below the blocking demand, J_k must start in time:

$$\sum_{\tau_i \neq \tau_k} W_{k \leftarrow i}(\Delta) < (M - m_k + 1)\Delta$$

Fixed classifies each interfering task τ_i relative to τ_k

Priority

$m_i \leq m_k$

$m_i > m_k$

higher

hplew

always blocks

hphw

conservative
body bound

lower

lplw

conservative
body bound

lphew

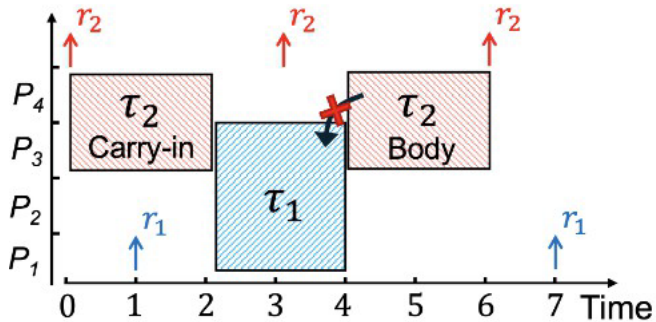
carry-in only

Analysis pessimism: Fixed counts both hphw/lplw worst cases even when they cannot co-occur.

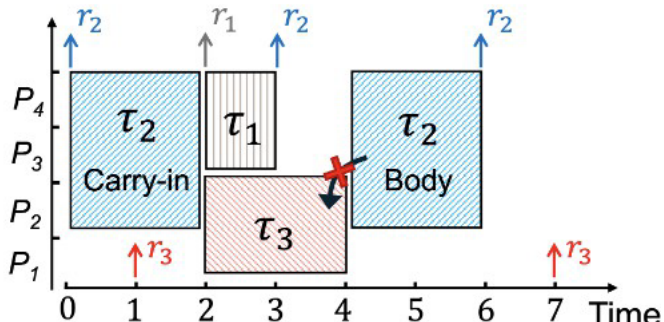
Fixed pessimism: mutually impossible worst cases

Execution examples

✗ Body job of *lplw* task τ_2 never blocks τ_1

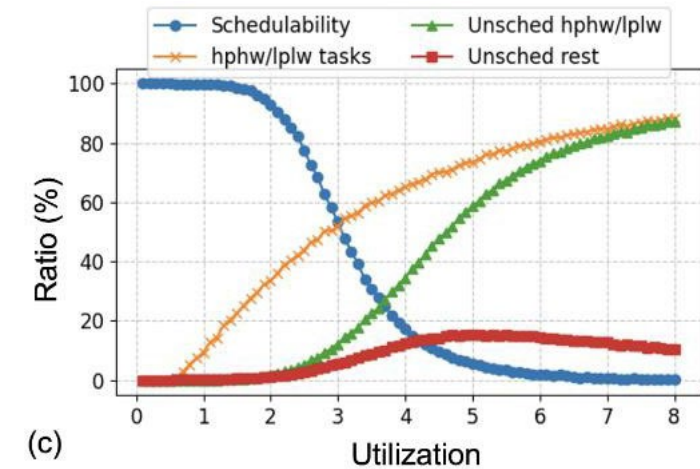


✗ Body job of *hphw* task τ_2 never blocks τ_3



Full body-job interference in both directions is counted twice

Random task sets



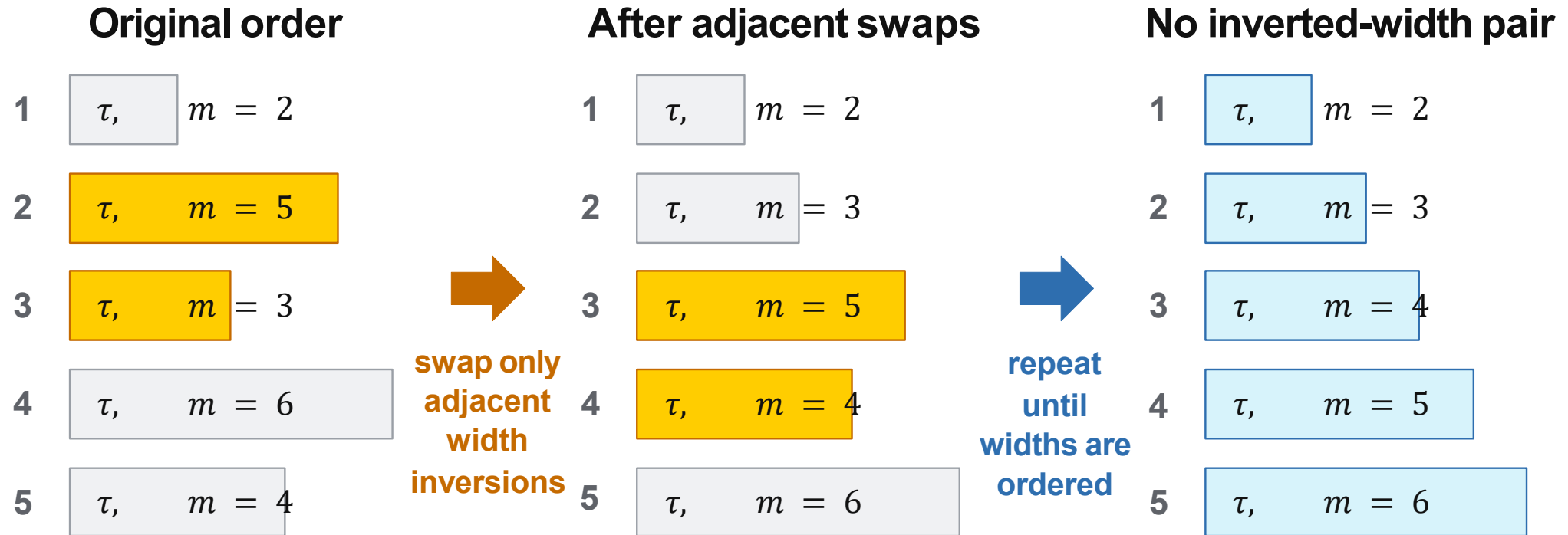
As hphw/lplw relations grow,
fewer tasksets are schedulable.

Verification consequence

A feasible flow set can be rejected because the test overestimates interference, so the system cannot pass verification.

Priority Swapping minimizes priority-order changes

Goal Eliminate every hphw/lplw pair while preserving as much of the original priority assignment as possible.

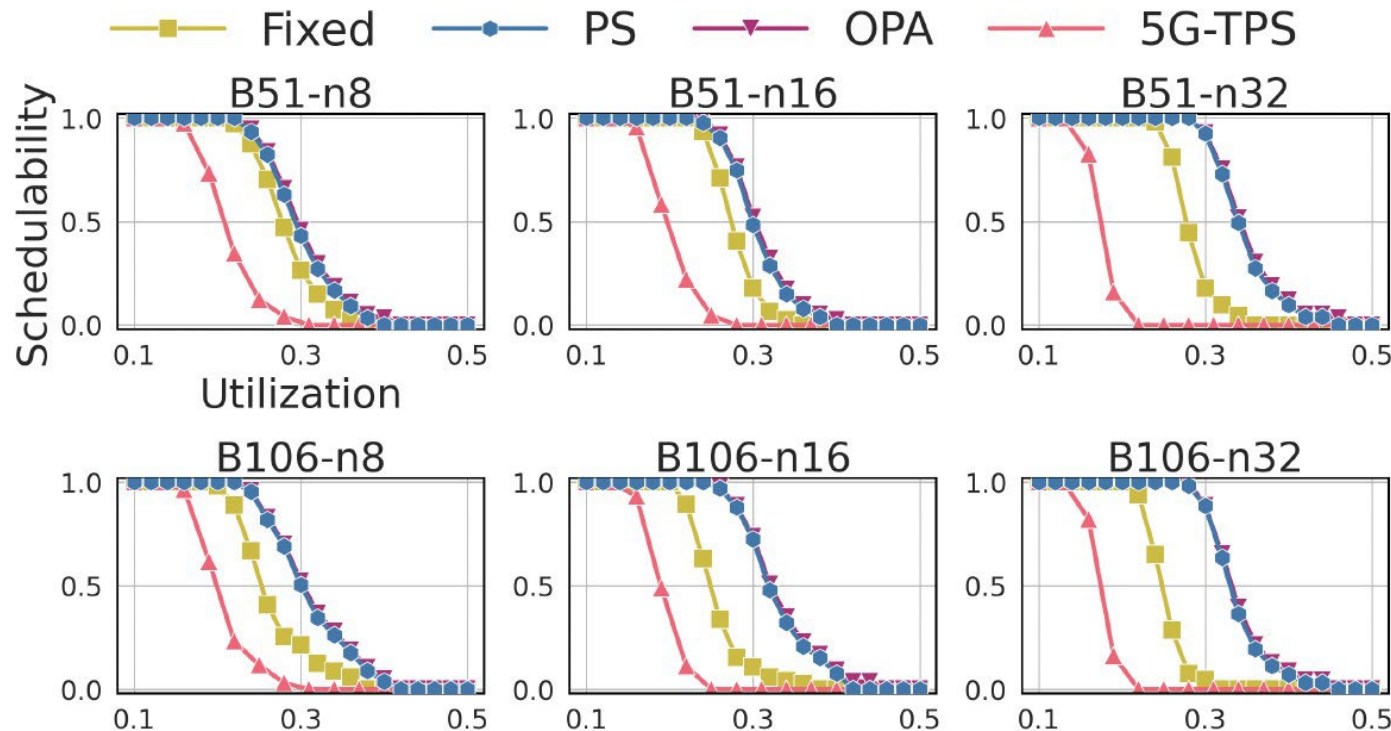


Minimum change Minimum Kendall-tau distance among valid orders.

Weak dominance If Fixed certifies π_0 , it also certifies the swapped order π .

Priority Swapping nearly matches OPA

$B \in \{51, 106\}$ RBs • $n \in \{8, 16, 32\}$ • 10,000 flow sets per point



Compared methods

- Fixed** SOTA test with original priorities
- PS** Adjacent swaps + one Fixed test
- OPA** Optimal assignment for Fixed; repeated tests
- 5G-TPS** Static hyperperiod schedule for periodic flows

81.2%

higher schedulability than Fixed at $n = 32$

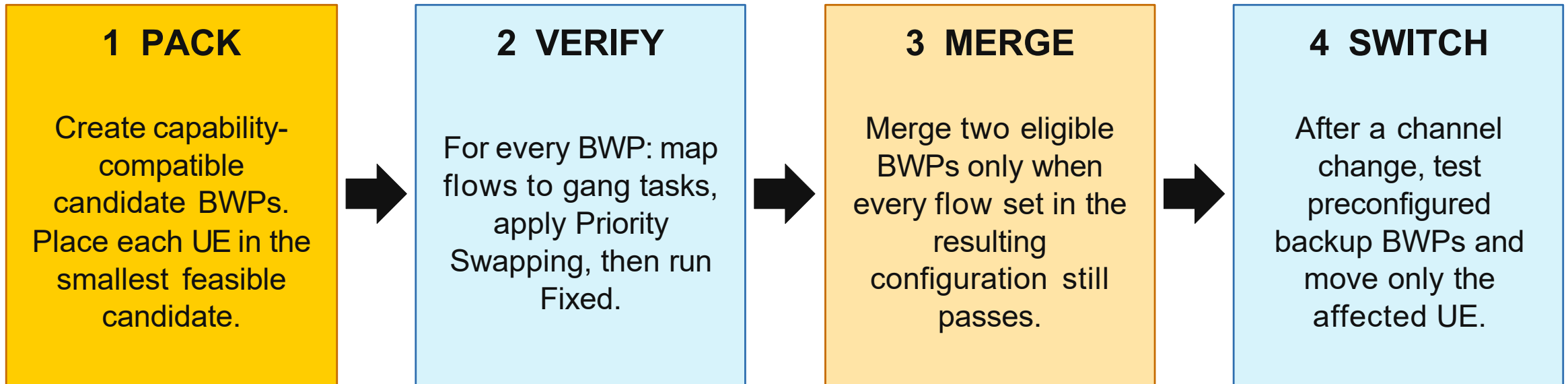
under 0.3%

maximum gap from OPA

The schedulability test gates BWP configuration

Initial configuration

Dynamic operation



The schedulability result is the decision gate

PASS: accept candidate FAIL: reject it and try the next placement

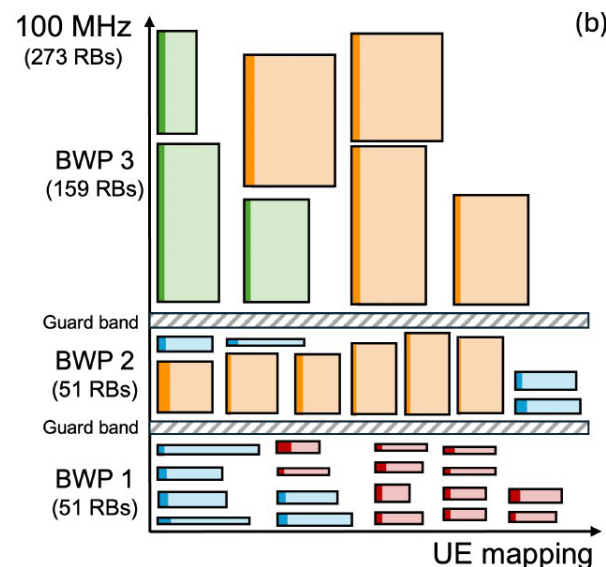
Every initial partition, merge, and runtime destination must pass the same intra-BWP test. Configuration never treats schedulability as an afterthought.

BWP configuration: case study and success rate

Smart-factory case study

(a) 5G smart factory use case

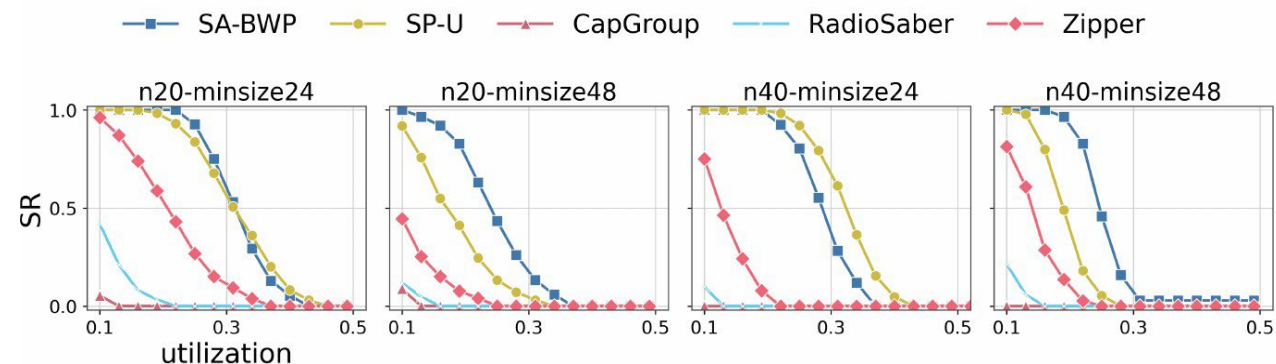
W2w replacement	# of UEs	3
	Period	2–60
	RB demand	40–90
	Trans time	2–10
100 MHz 273 RBs		
AGV control	# of UEs	10
	Period	20–200
	RB demand	25–70
	Trans time	2–8
60 MHz 162 RBs		
C2c TSN	# of UEs	10
	Period	8–16
	RB demand	3–10
	Trans time	2–8
60 MHz 162 RBs		
Motion control	# of UEs	12
	Period	1–4
	RB demand	2–5
	Trans time	1–3
20 MHz 51 RBs		



100 MHz carrier: 273 RBs

Three BWPs of 51, 51, and 159 RBs with two 6-RB guard bands. Every UE fits its capability limit and every BWP passes verification.

Configuration success ratio



Compared with

SP-U: partitioned gang scheduling

CapGroup: group identical capability tiers

RadioSaber and Zipper: RAN slicing baselines

SA-BWP stays strong at a 48-RB minimum by retaining parallel intra-BWP execution.

Takeaways

01

BWP resolves hardware mismatch

The OAI testbed confirms that a capability-compatible BWP restores attachment and bounds the RBs available to each UE.

02

Priority Swapping improves verification

Downlink K-repetition yields NP-FP gang tasks. Adjacent swaps remove a major pessimism source with minimum priority disruption and weak dominance.

03

The schedulability test gates configuration

Every partition, merge, and backup destination must pass Priority Swapping plus Fixed before the system accepts it.

Thank you! Questions?