Introduzione ai sistemi di comunicazione acustica per reti sottomarine

Loreto Pescosolido, Chiara Petrioli

Reti Wireless

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SAPIENZA
UNIVERSITÀ DI ROMA

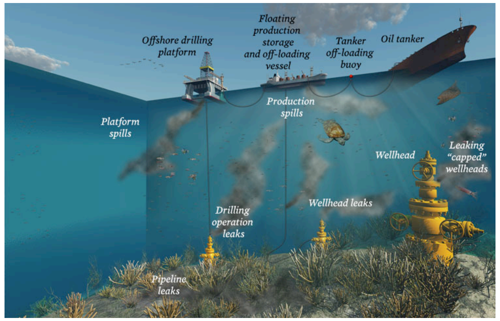
Sommario

- Underwater Acoustic Sensor Networks (UASNs): Motivazioni e applicazioni
- Confronto tra propagazione delle onde radio (in aria e in acqua) e onde acustiche.
  - Il problema dell'interferenza
  - Curvatura dei percorsi: il fenomeno delle shadow zones
- Risposta in frequenza: variabilità nel tempo e nella frequenza dei canali
- Tipi di rete particolari: data-muling e DTN
- Confronto tra protocolli

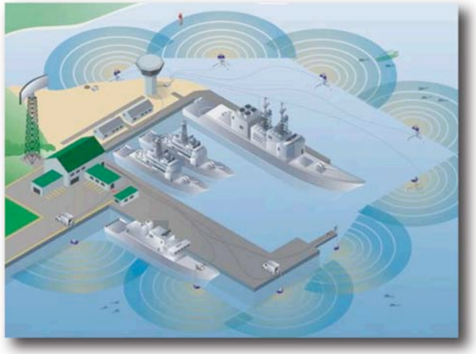
Underwater Acoustic Sensor Networks (UASNs): Motivazione e applicazioni

Monitoraggio di infrastrutture critiche

Impianti di Estrazione e condotte sottomarine



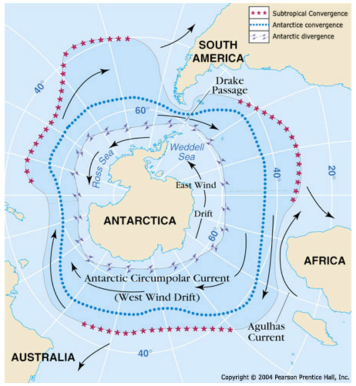
Border control: porti, cantieri, zone protette



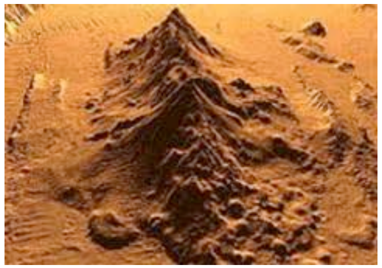
Monitoraggio ambientale

Temperatura e salinità

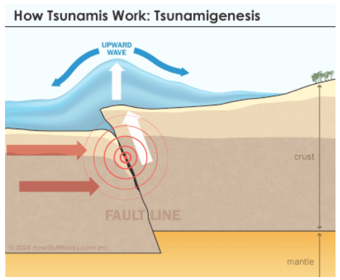
Correnti



Vulcani e sismi



Tsunami alert

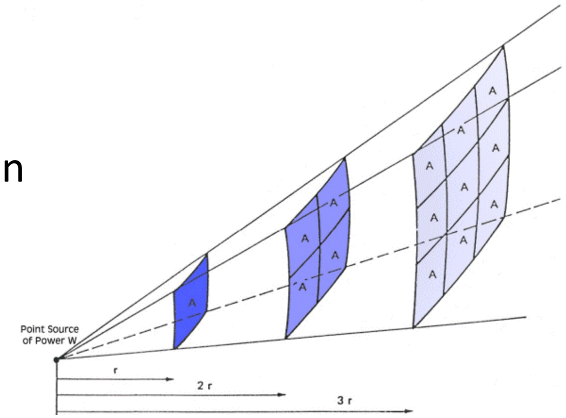


Flora sottomarina

Propagazione delle onde

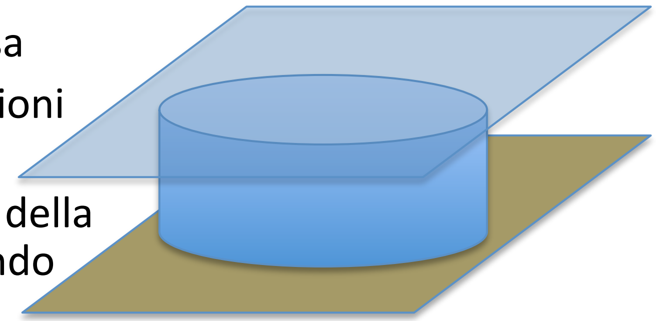
Onde radio nel vuoto

- Velocità: $3*10^{8}$ m/sec
- In presenza di un ostacolo l'onda viene parzialmente riflessa
- In assenza di ostacoli, l'onda si propaga in linea retta (fino ad un certo limite).
- La potenza incidente su uno stesso elemento di superfice si attenua con l'inverso del quadrato della distanza ($\sim 1/r^2$).



Onde acustiche in acqua:

- Velocità: $1{,}5*10^{3}$ m/sec
- In presenza di un ostacolo l'onda viene parzialmente riflessa
- In assenza di ostacoli, l'onda può curvarsi, a causa di variazioni di pressione e temperatura.
- Grazie alla ricurvatura dei raggi verso il basso in prossimità della superficie, oltre una certa distanza, l'onda si propaga secondo una legge di attenuazione cilindrica invece che sferica. La potenza decade (in prima approssimazione) come 1/r.



…in realtà:

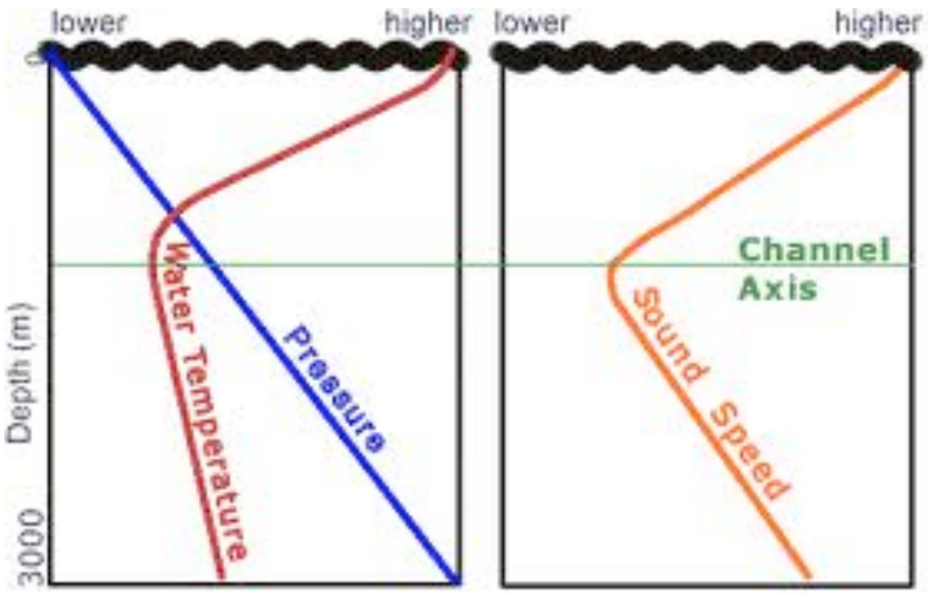
$$\text{channel attenuation: } A(r,f) = A_0 a(f)^r \frac{1}{r^k}$$

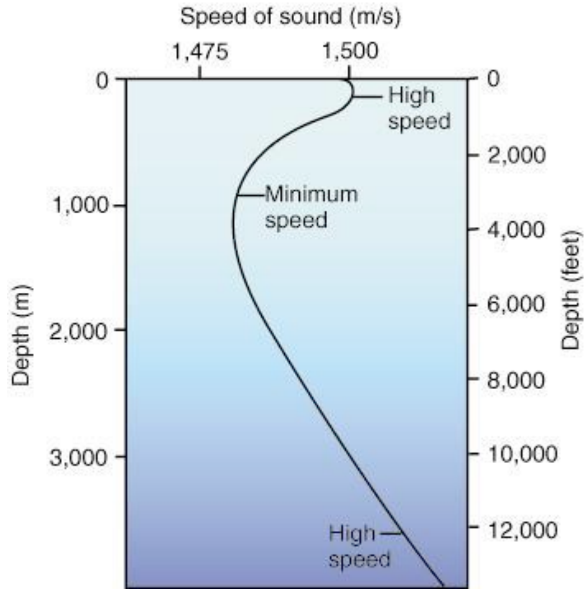
$$\text{a(f) = absorption coefficient: increases with f}$$

Propagazione delle onde

SOUND SPEED PROFILE

- Esprime la velocità di propagazione dell'onda acustica alle diverse profondità
- E' funzione della temperatura e della pressione alle diverse profondità





- Determina la curvatura dei "raggi acustici"

Propagazione delle onde

Effetti del SOUND SPEED PROFILE

La diversa velocità a profondità diverse provoca la curvatura dei raggi, in particolare:

- Propagazione cilindrica:

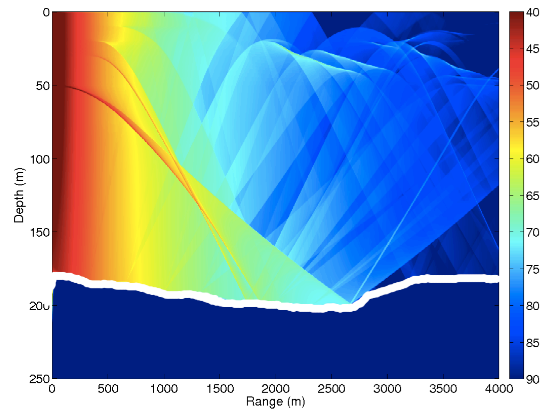
  l'energia dell'onda si espande in due dimensioni invece che tre perché parte dei raggi che vanno verso la superficie vengono ripiegati verso il basso e quindi la loro energia viene "trattenuta" nello strato d'acqua. Il suono si propaga facilmente anche per centinaia di chilometri.

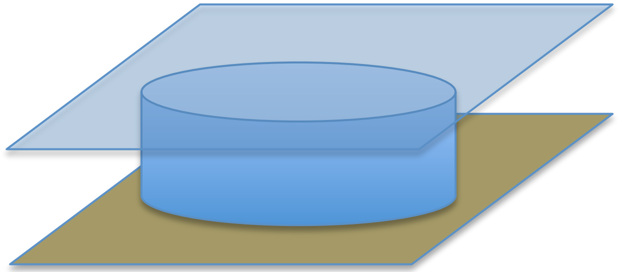
- Fenomeno delle shadow-zones

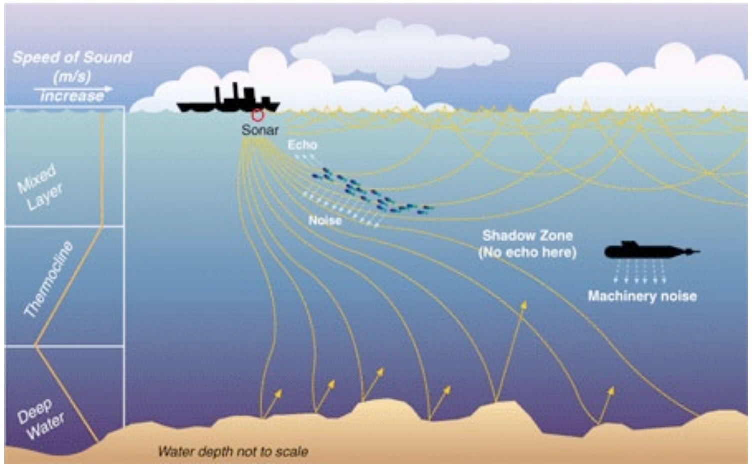
Inoltre:

Variabilità temporale dovuta a:

  – Correnti
  – Moto ondoso sulla superficie





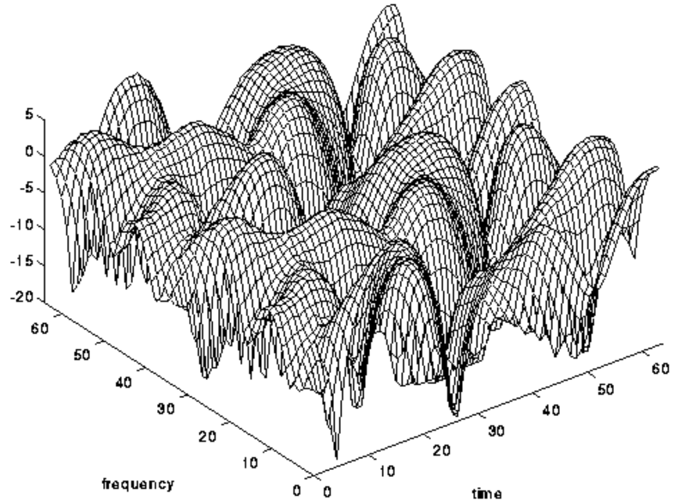


Risposta in frequenza

Gli effetti descritti, provocano comportamenti diversi su frequenze diverse

- Il canale acustico sottomarino presenta rilevanti variazioni sia nel tempo che nella frequenza
- Time spread e doppler spread

→ difficile ottenere sotto-canali ortogonali



Notare che i disturbi possono provenire da sorgenti acustiche (navi) diverse da modem.

→ L'interferenza tra nodi è uno dei problemi maggiori per le UASNs, (anche a causa delle lunghe distanze di propagazione).

Protocolli e reti UASNs

→ I protocolli per UASNs devono essere, per quanto possibile, adattivi

Inoltre:
La presenza delle shadow zones, introduce la necessità di reti di tipo particolare

- Data muling
- Delay-Tolerant Networks

(possibili anche al fatto che i requisiti in termini di data-rate e delay sono molto meno stringenti rispetto a reti terrestri)

MAC comparison

- UASNs MAC characteristics:
  - Nodal synchronization
  - Use of control packets for channel acquisition
  - Ways for accessing the channel
  - Use of ACKs
  - Slotted or unslotted time

The considered protocols are:

- ALOHA
- APCAP (Adaptive Propagation-Delay Collision Avoidance Protocol)
- DACAP (Distance Aware Collision Avoidance Protocol)
- PDAP

ALOHA

Random Access with CSMA and backoff:

- If the channel is idle, the node transmits
- If it is busy, it waits for a backoff time

Possible use of ACKs,

- Limit of (2*delay + acktime) for retransmission
- Backoff time ~ U[0,T] with T=2^txRetry

Does not require synchronization

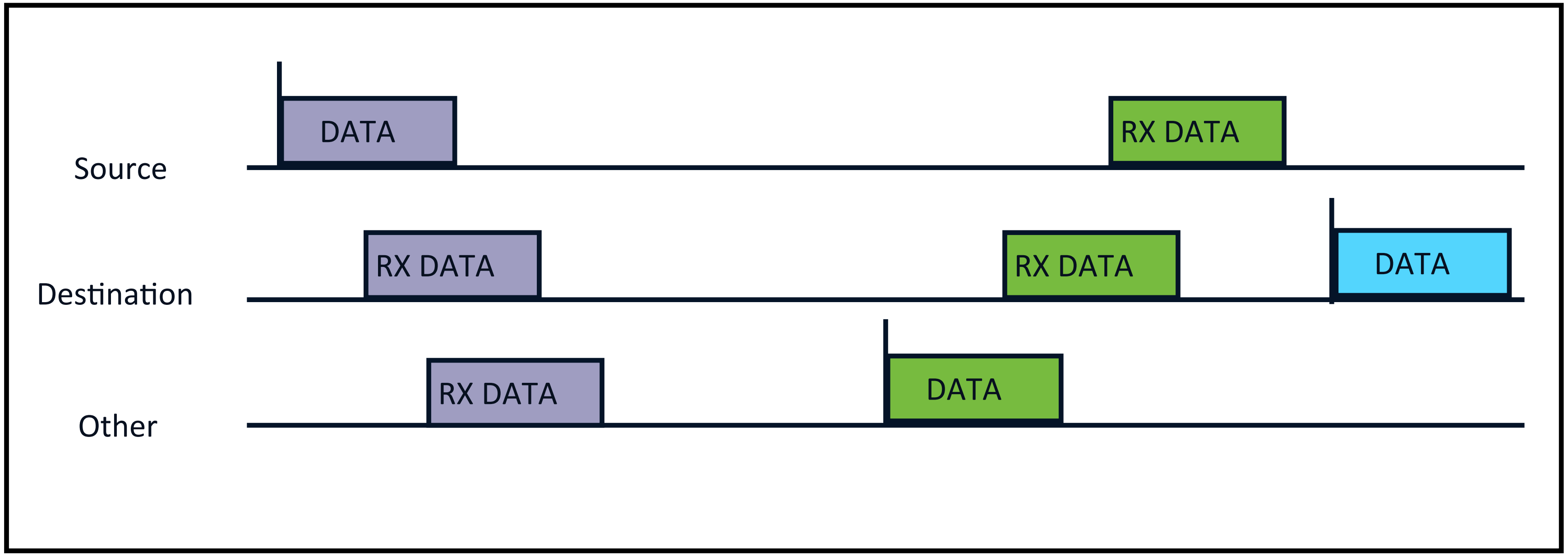
Slotted ALOHA

- slot duration is an important parameter
- time_slot = β*maxDelay + datatime

Requires synchronization

ALOHA

- Nodes are not synchronized
- Uses carrier sensing.
- No control packets fo channel acquisition



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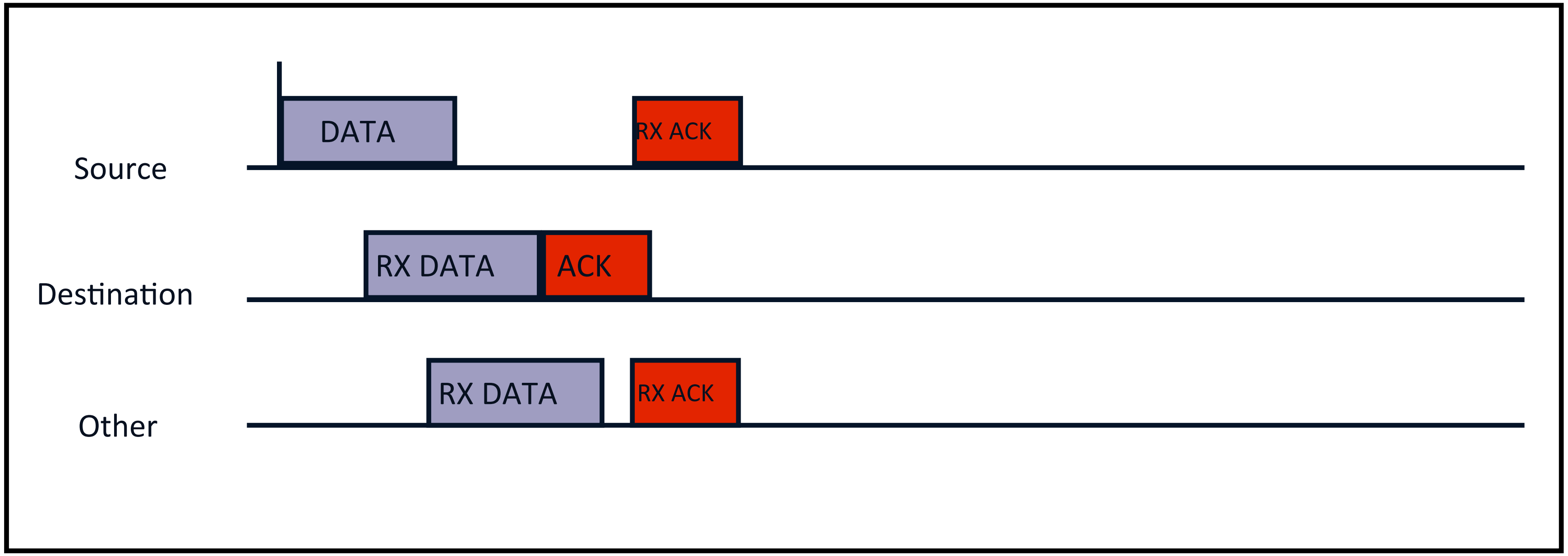
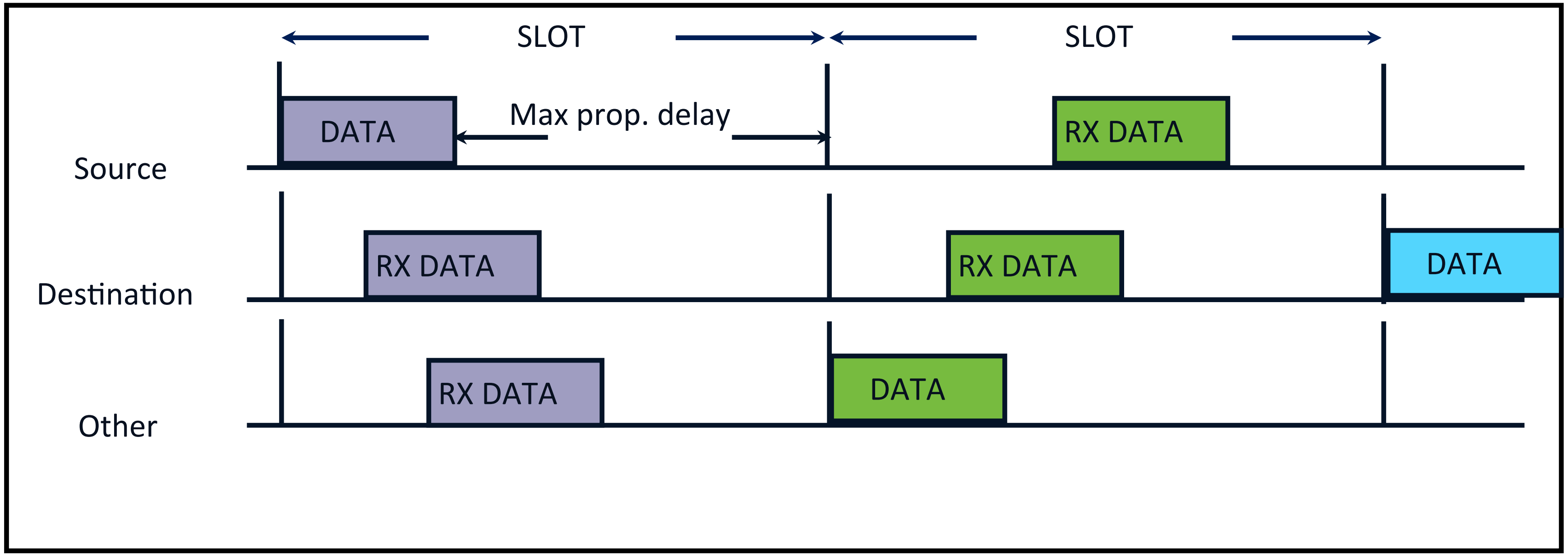


Slotted ALOHA

Nodes are synchronized
Uses carrier sensing
Transmissions start at the beginning of the slot
No control packets for channel acquisition



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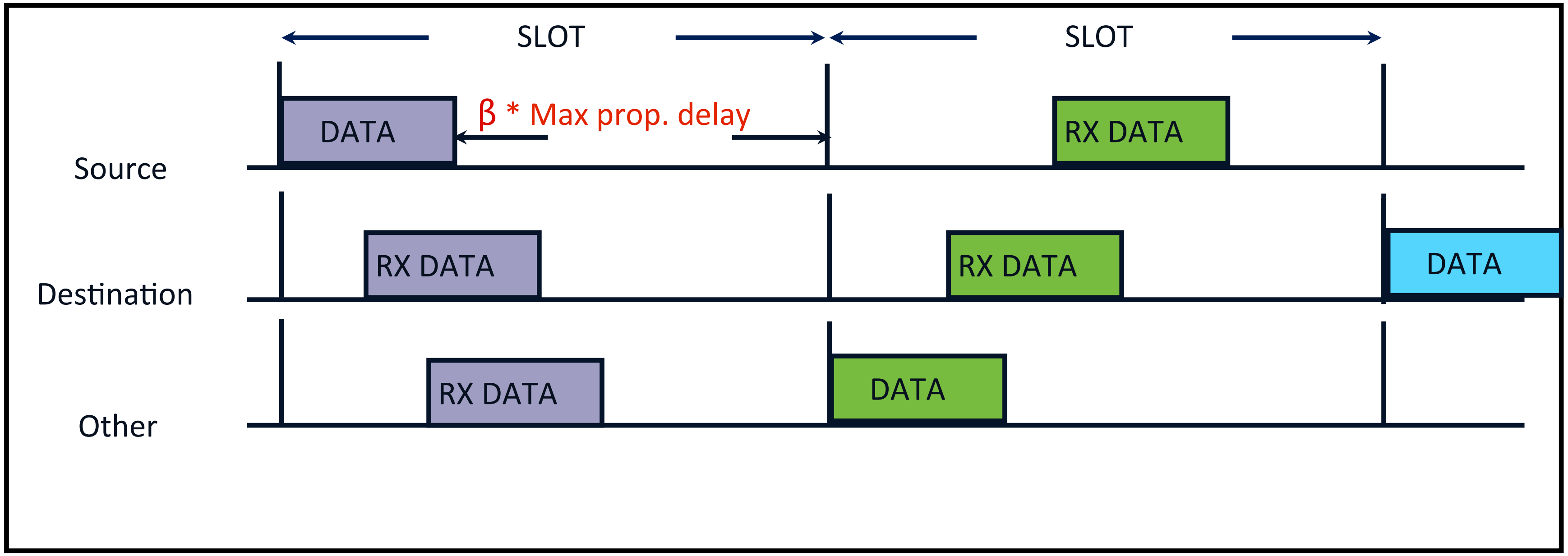

$\beta = 0.5$

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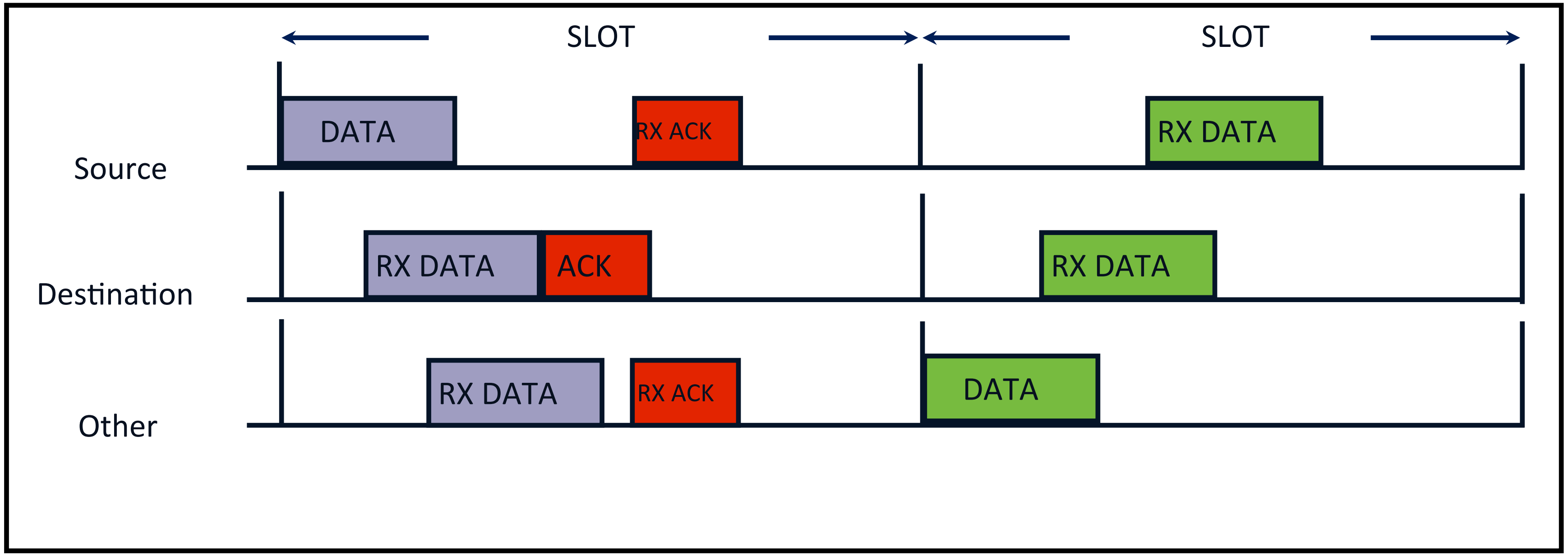


SLOT = TxTime(DATA) + TxTime(ACK) + Max propagation delay

APCAP adaptive propagation delay collision avoidance protocol

Random access. Based on RTS-CTS *with the use of windows*

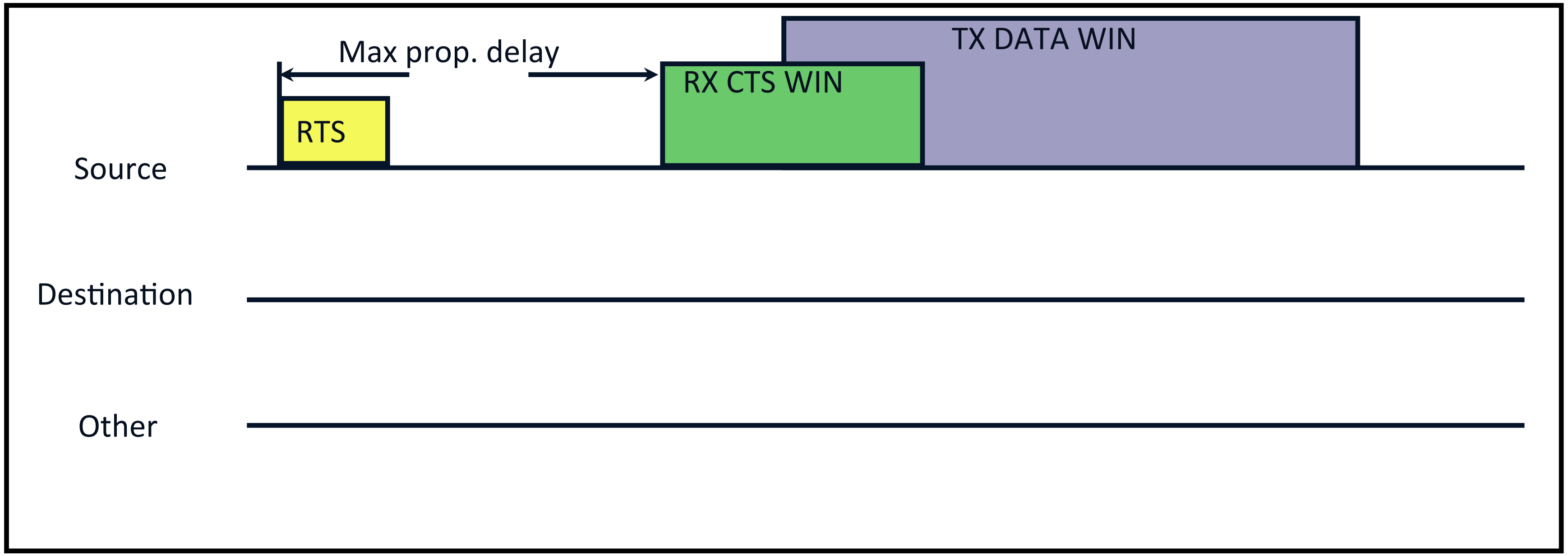
The sender indicates a CTS_window for the reception of the CTS and a data_window for the data sending

→Negotiation of the transmission time

Interference is reduced through suitable setting of the potential interferers Network Allocation Vectors (NAV) so as to exclude the CTS_window and DATA_window from transmission

APCAP adaptive propagation delay collision avoidance protocol

- Nodes are synchronized
- RTS/CTS-based channel acquisition (with timestamp)
- Each node has its own schedule
- Source and destination negotiate packet transmission timing



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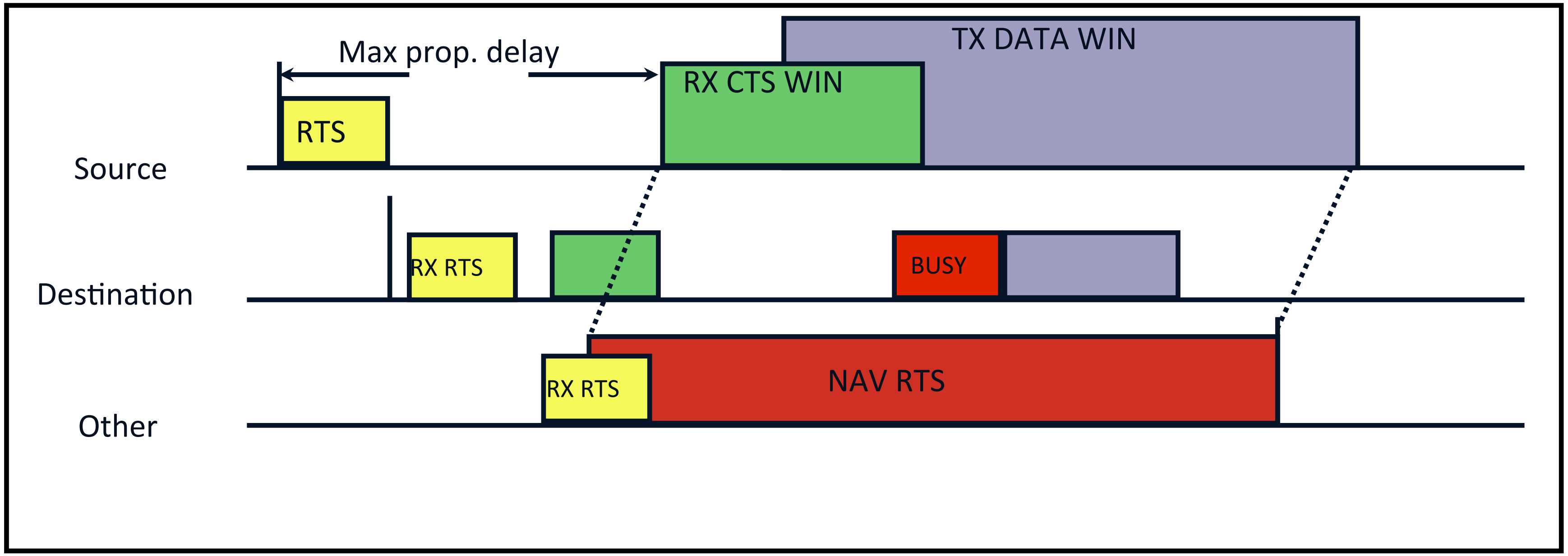

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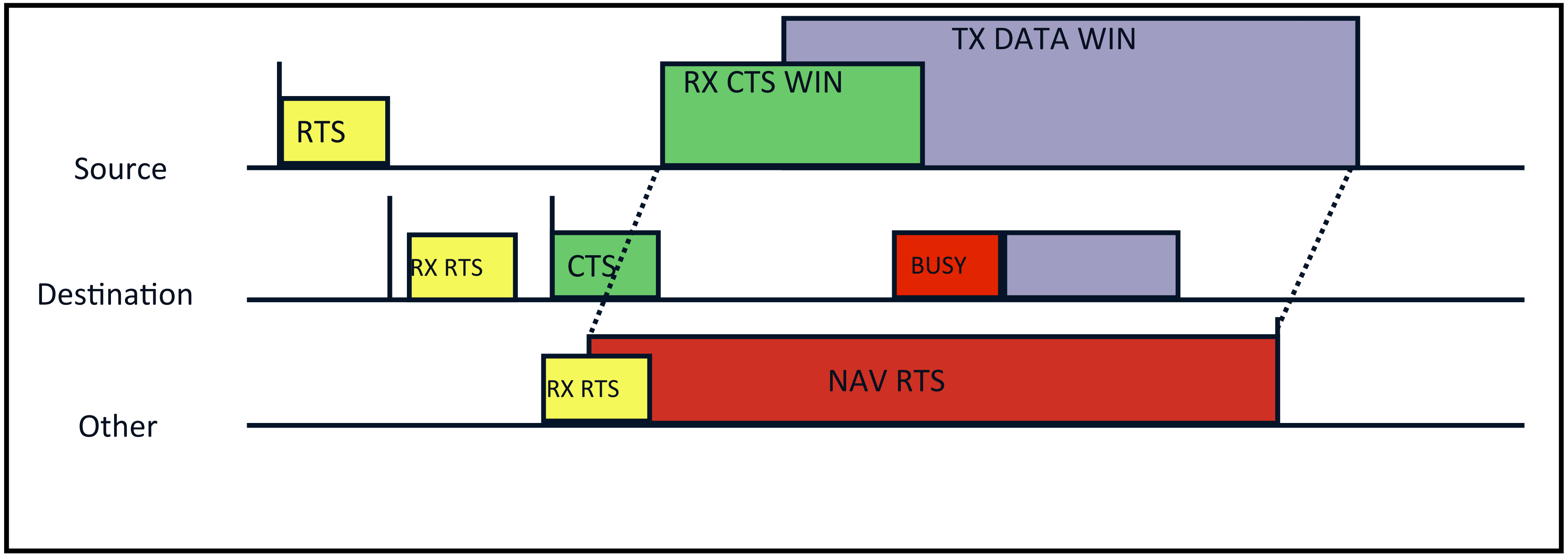

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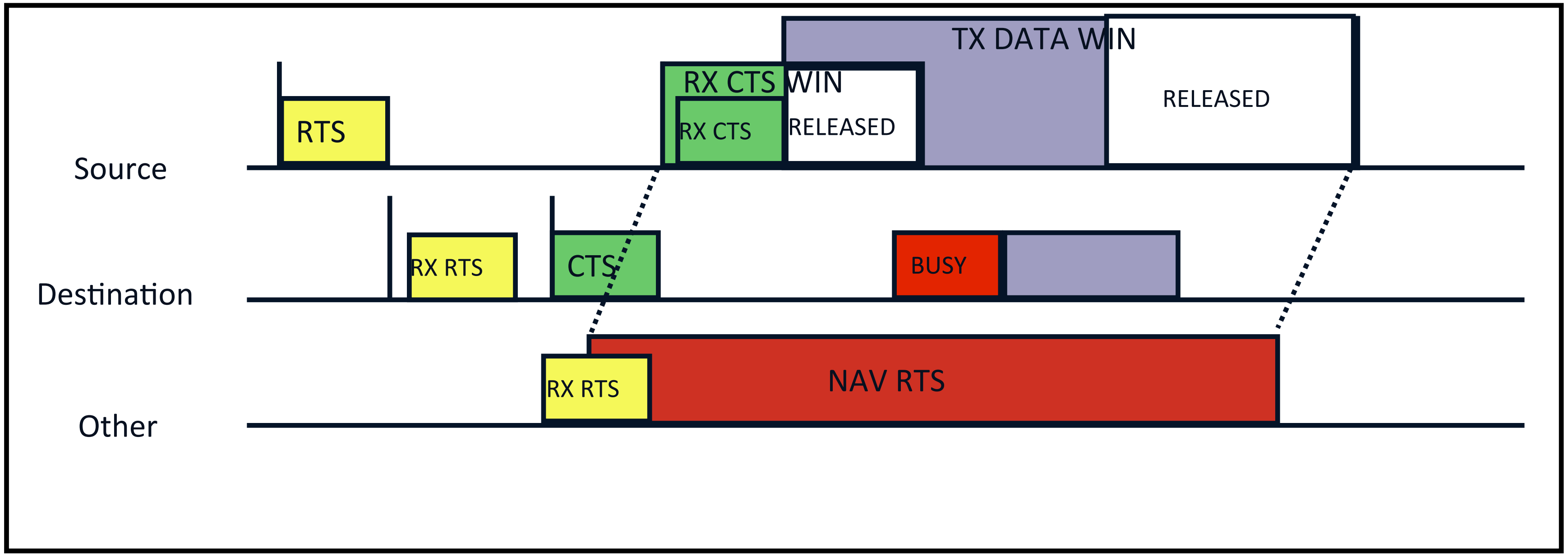

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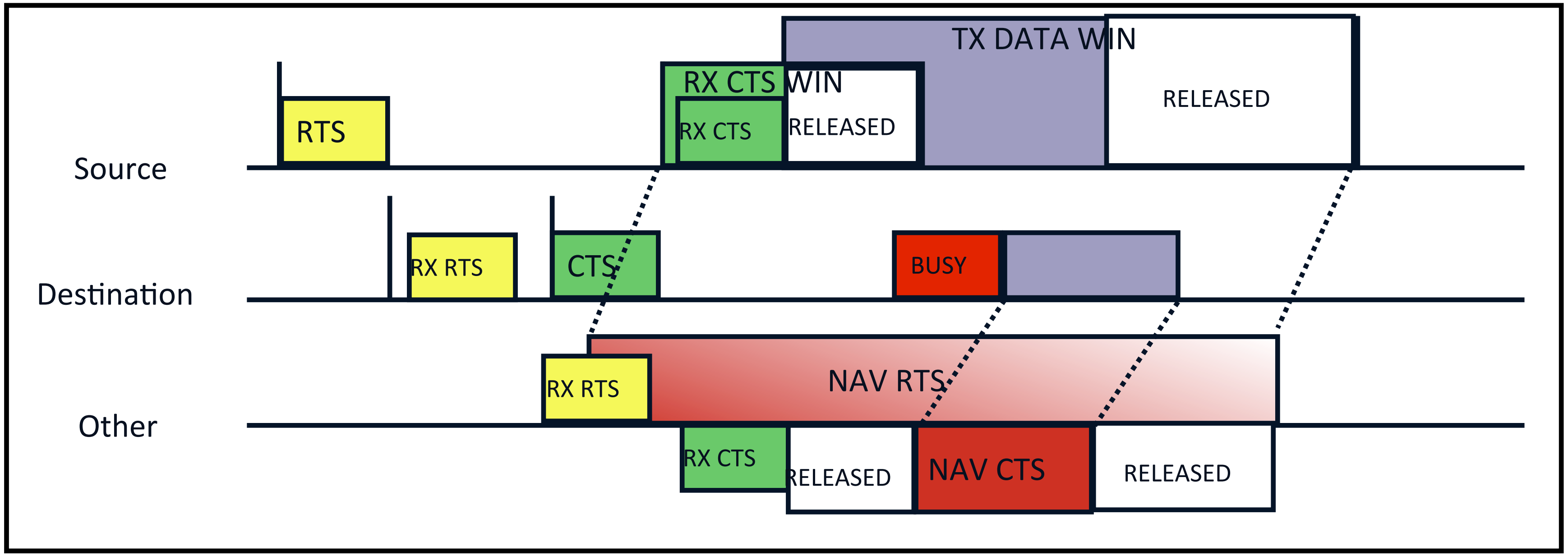

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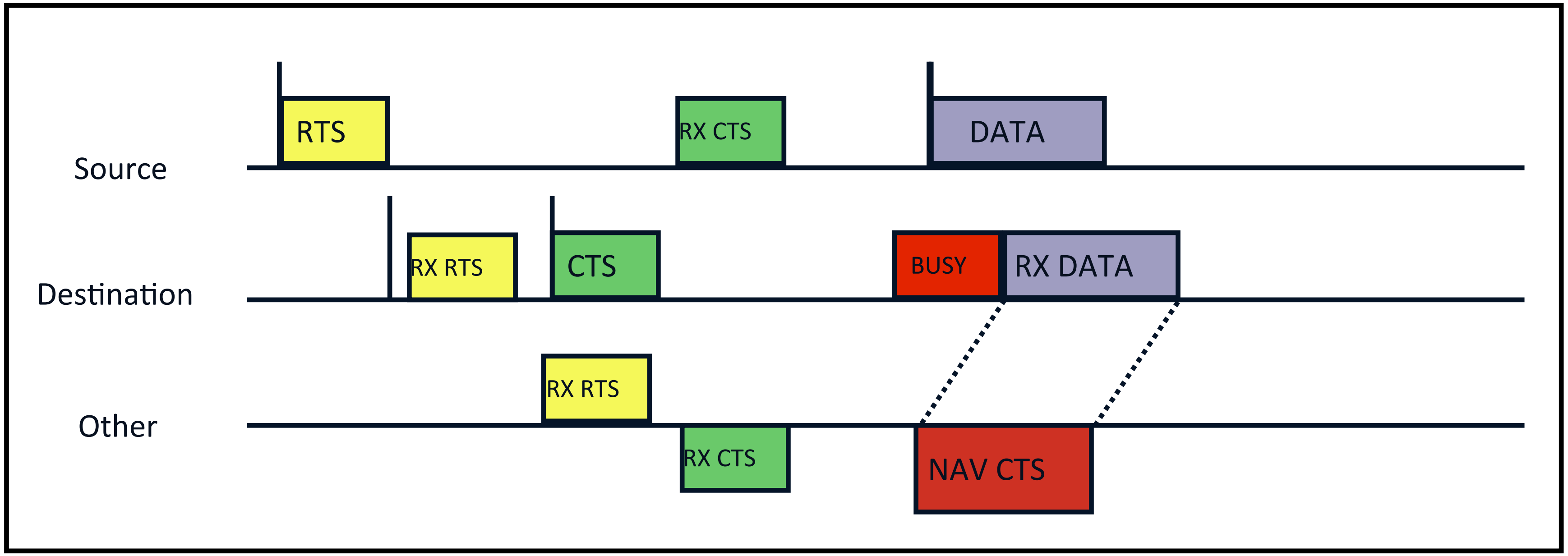

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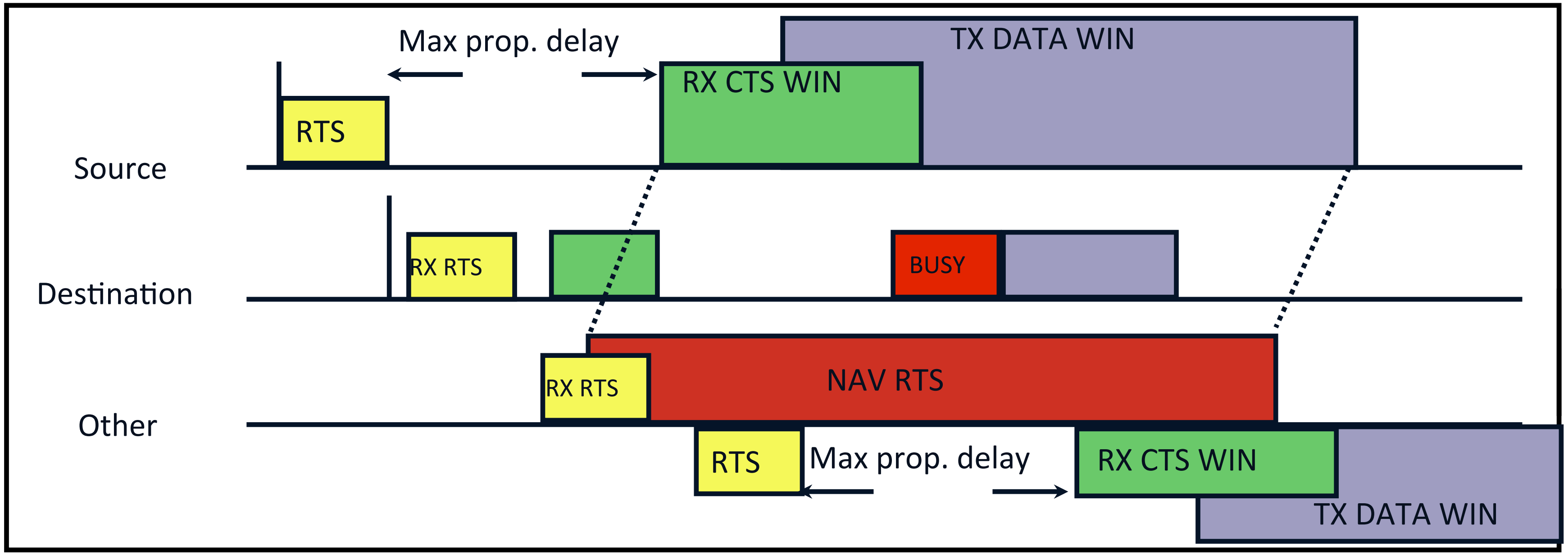

DACAP distance aware collision avoidance protocol

Random access. Based on RTS-CTS

- Differently from APCAP, the replies are instantaneous
- Collisions are avoided through the insertion of a WARNING time between the reception of the CTS and the actual data transmission.
- During this interval, the receiver can send a WARNING packet if it hears any control packet from other nodes.
- Likewise the sender can overhear control packets.
- If the sender receives a warning or listens to other control packets during the warning time, it aborts the data transmission.
- The challenge is the best choice of the WARNING time, which is performed through an inference of the sender-receiver distance obtained by measuring the RTS CTS round trip delay

No synchronization required

DACAP distance aware collision avoidance protocol

- Nodes are not synchronized
  RTS/CTS-based channel acquisition
  Distances between nodes are measured based on control packets RTT
  Uses a warning period before transmitting for avoiding collisions

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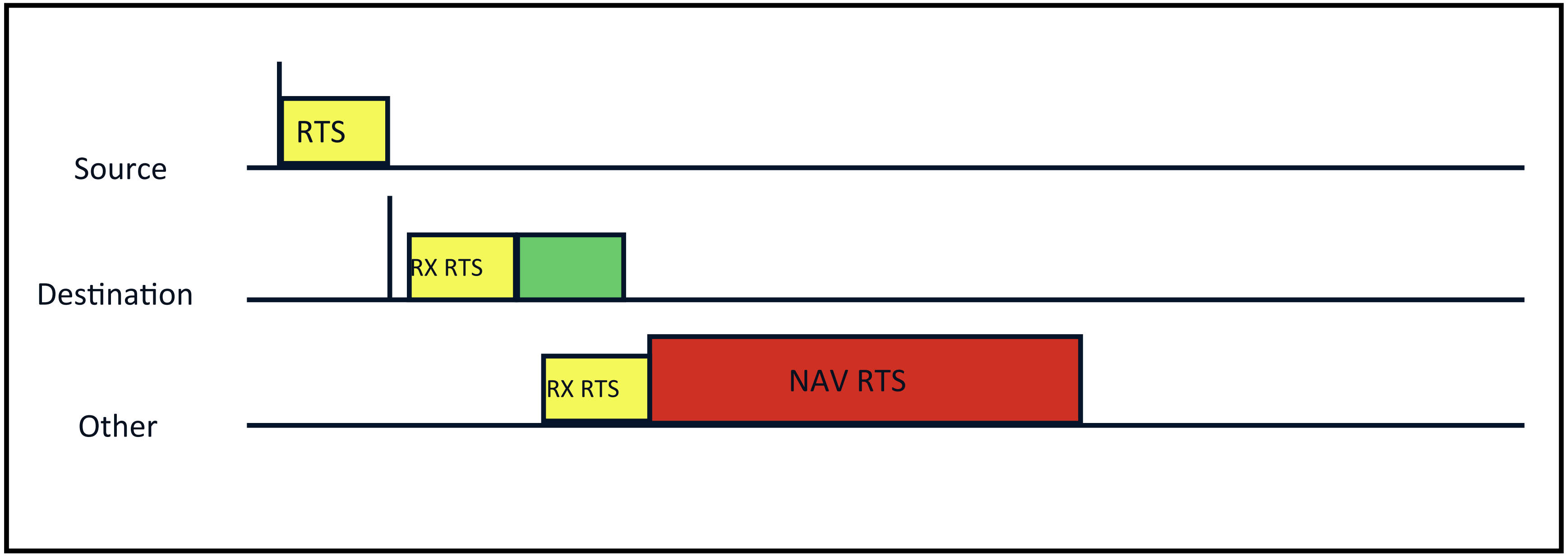

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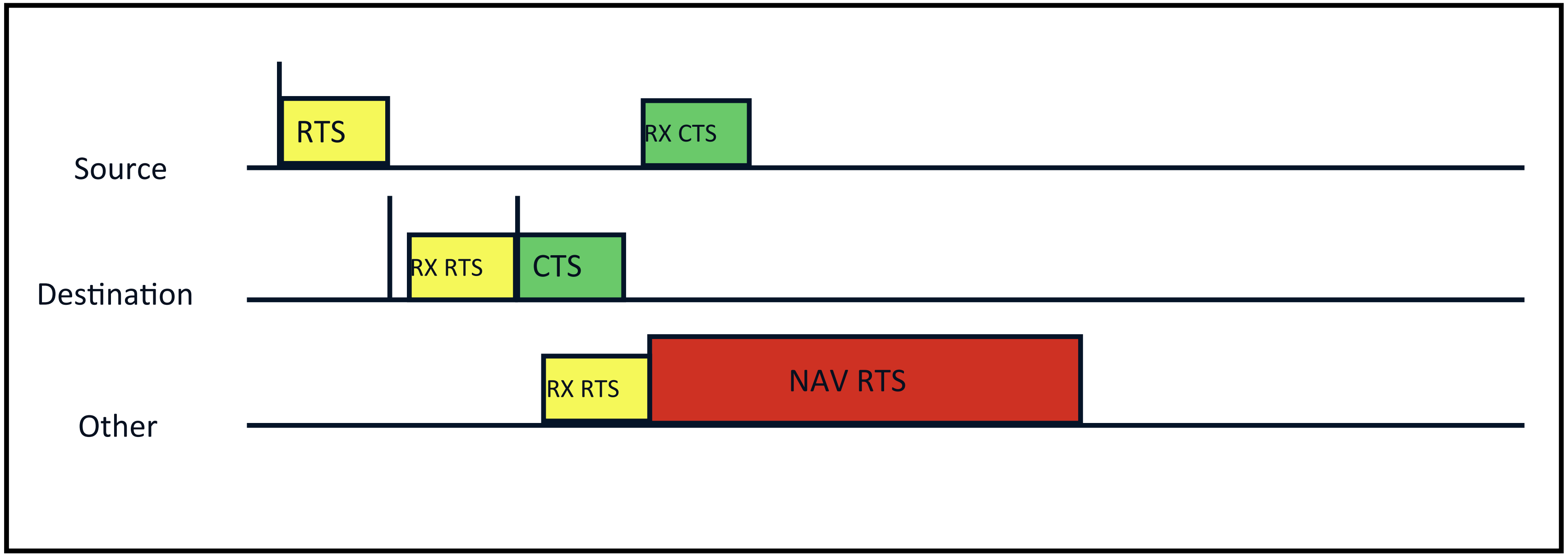

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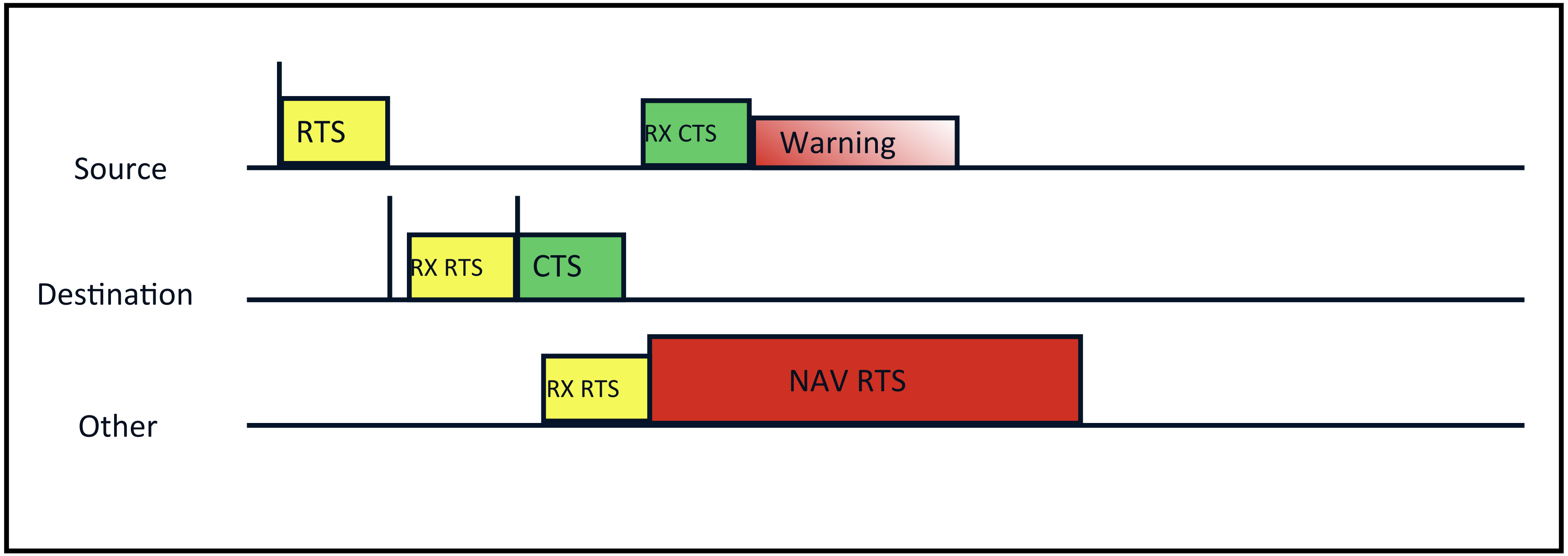

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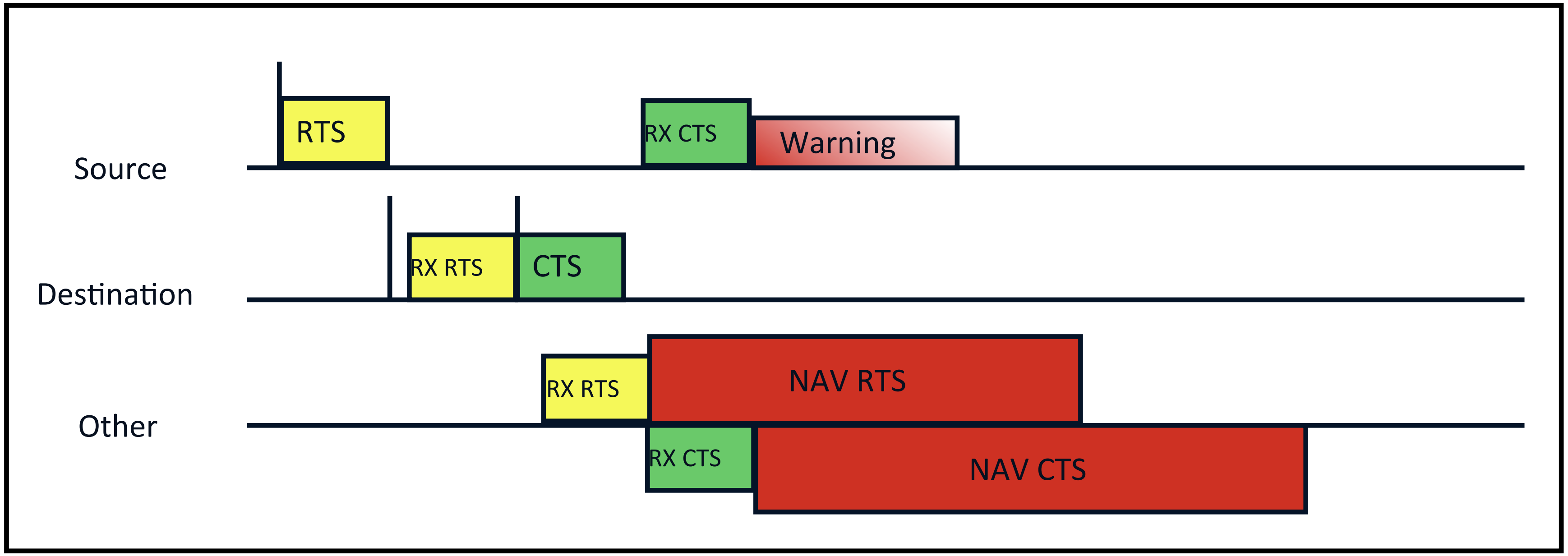

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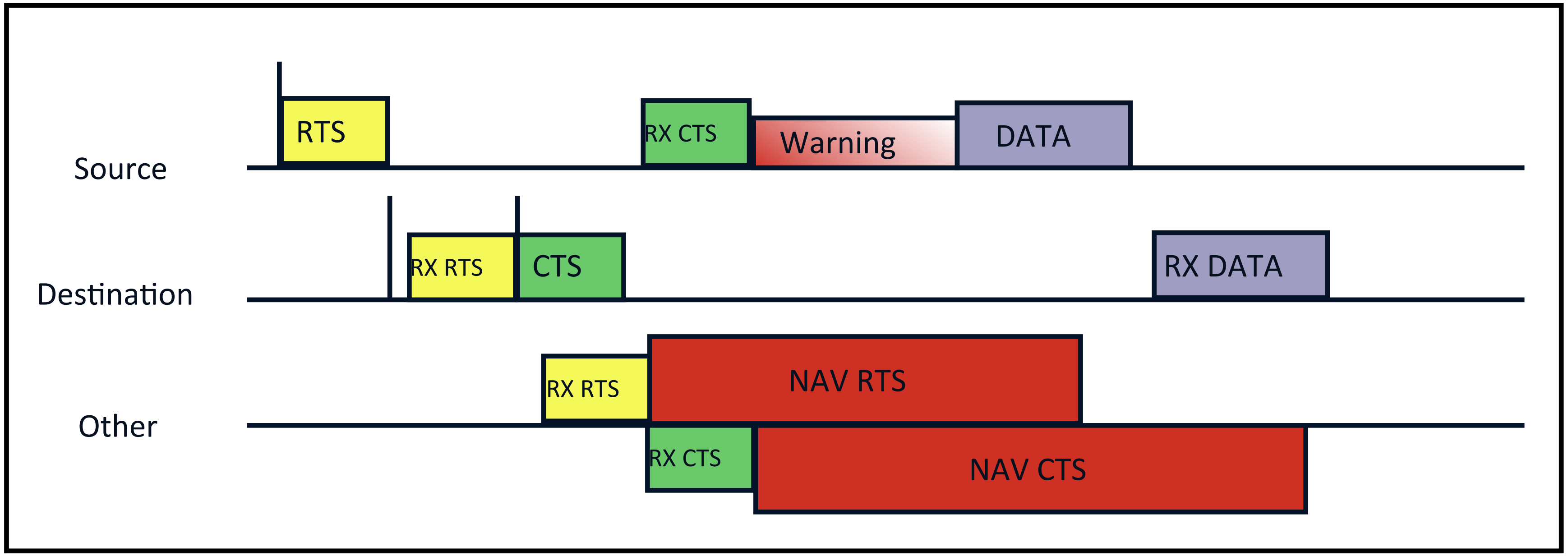

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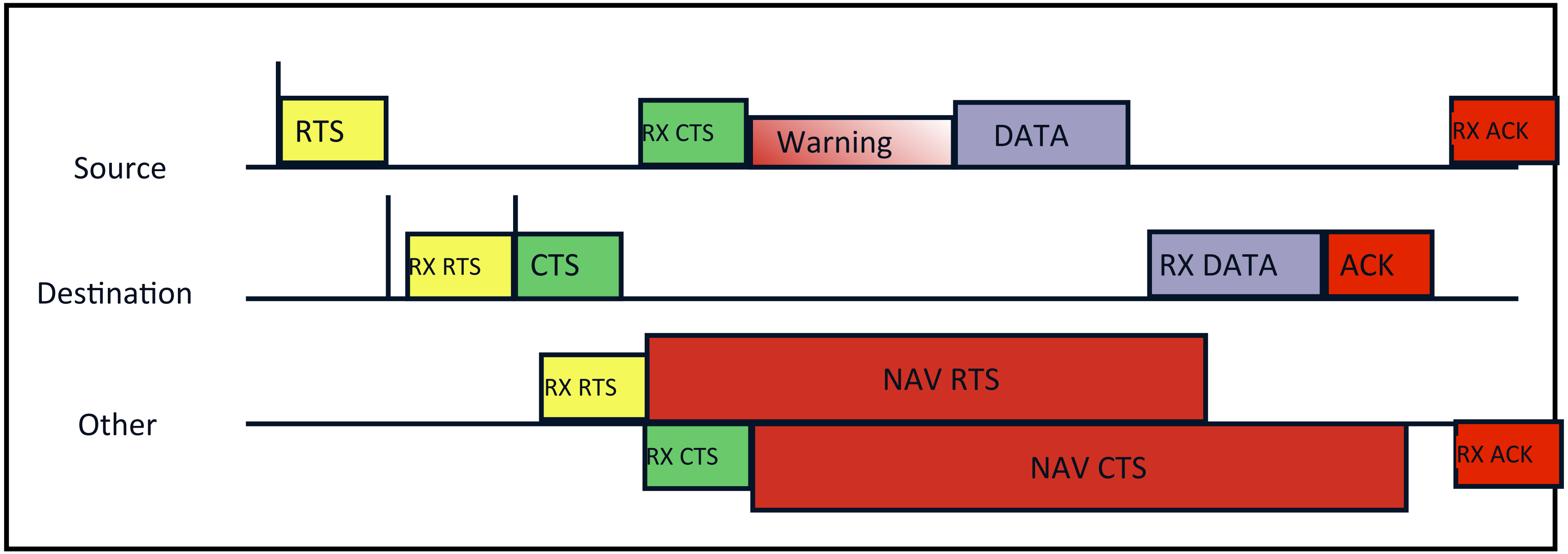


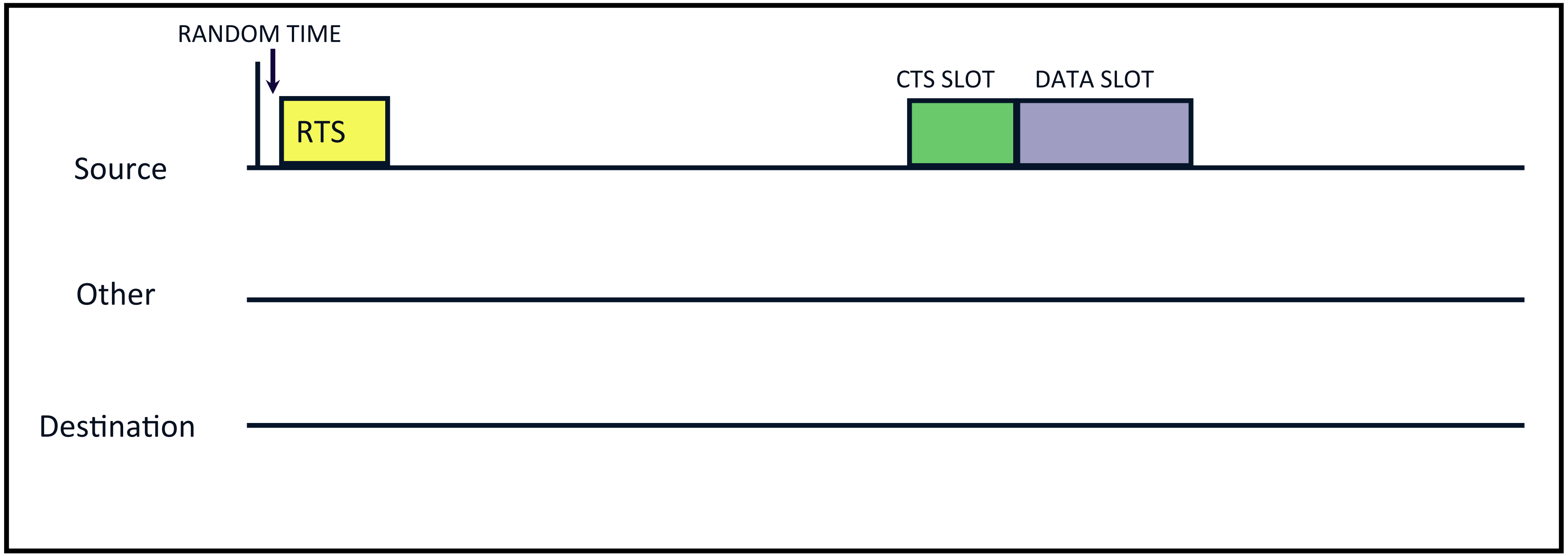
PDAP propagation delay aware protocol

Nodes are synchronized

RTS/CTS-based channel acquisition

RTS/CTS timestamp are used to compute distance between nodes
Infer distance between source and destination

Uses random time and backoff to avoid nodes synchronization and collisions
Every node has its own schedule and interleaved communications are possible



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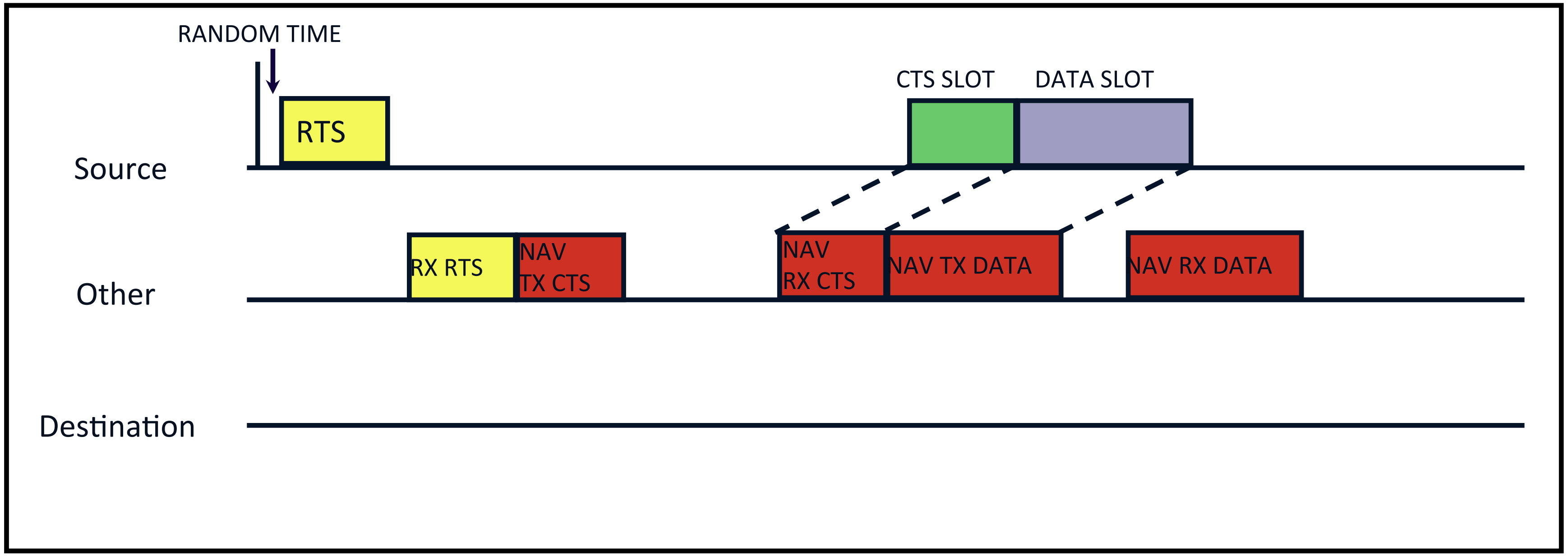

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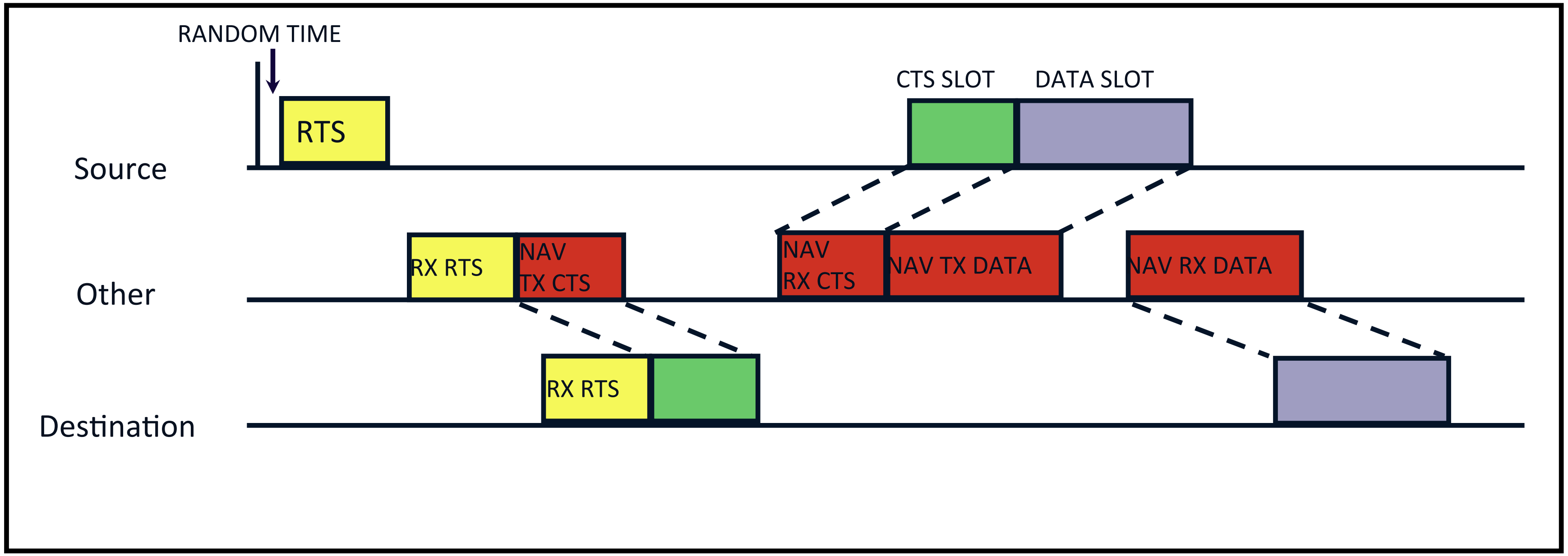

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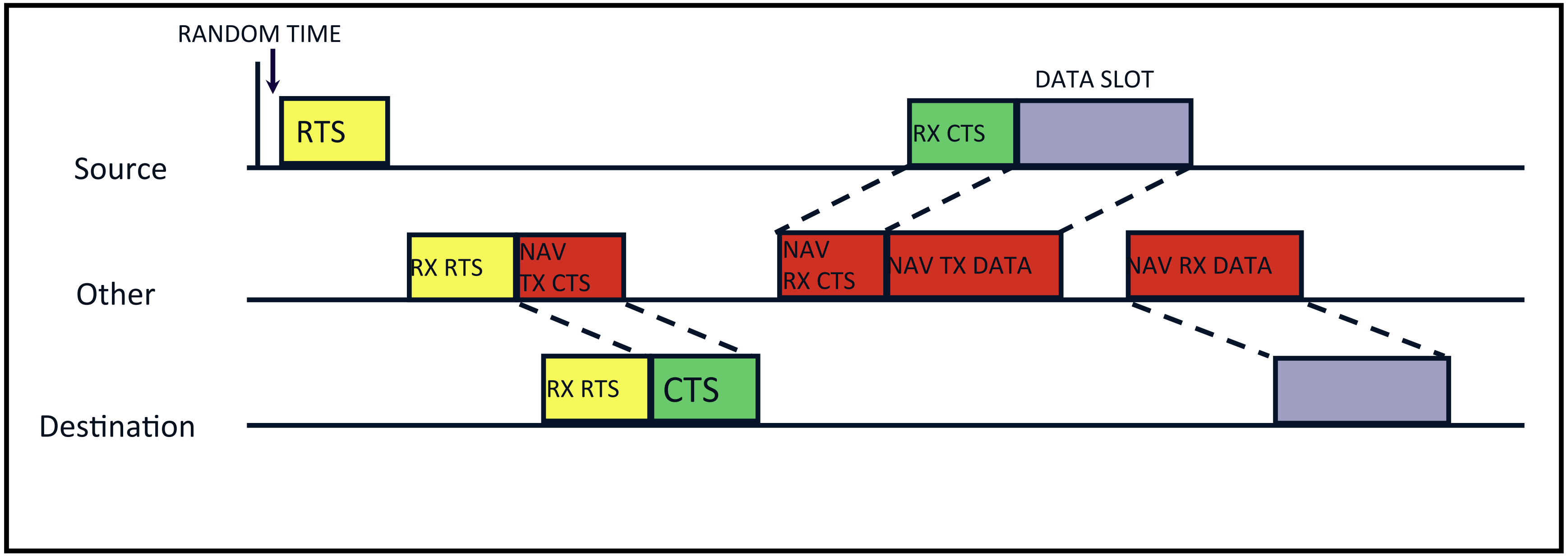

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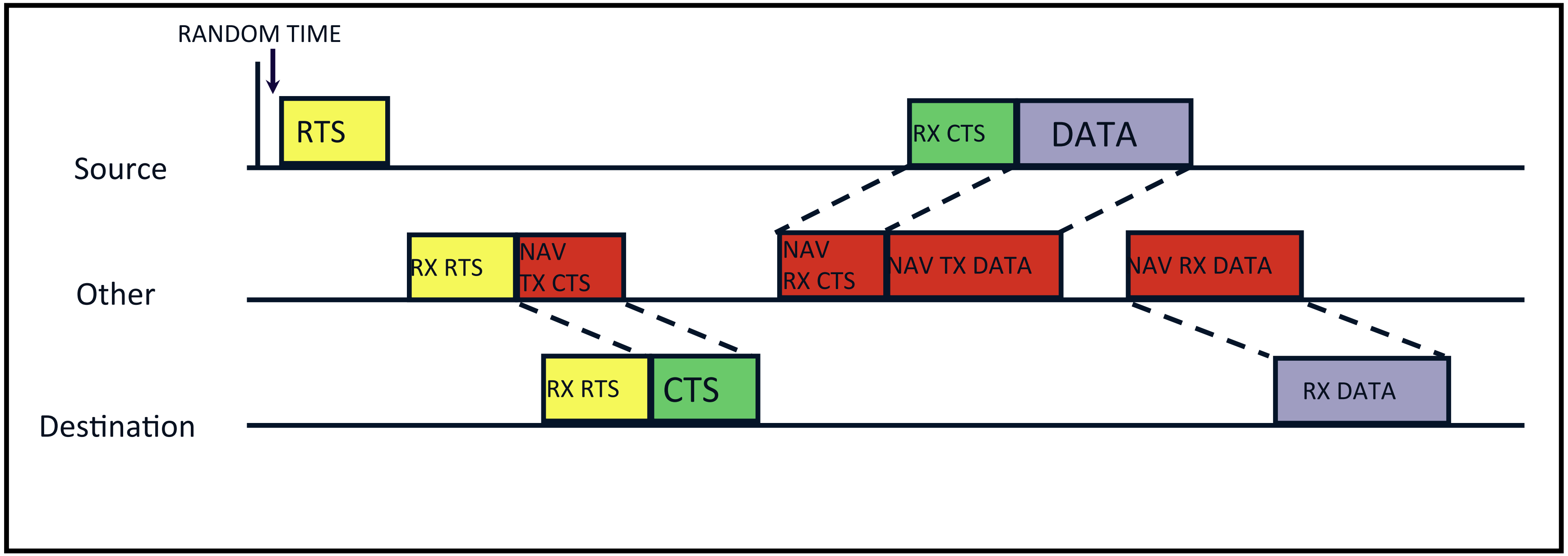

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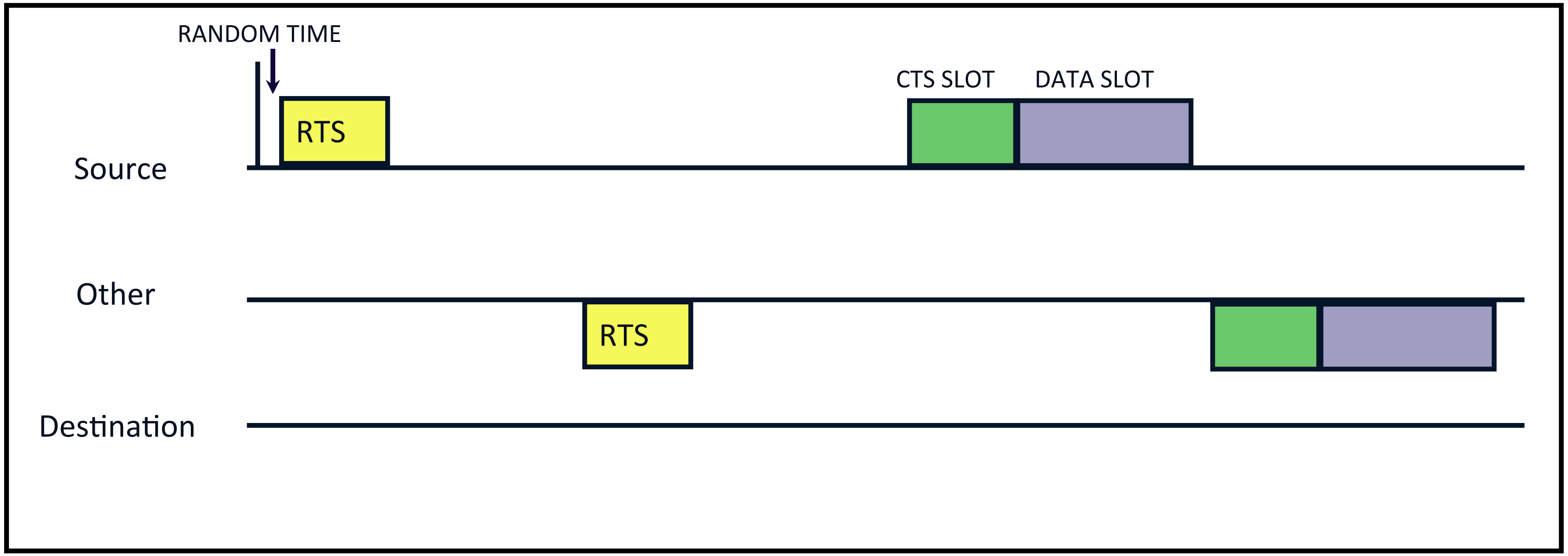

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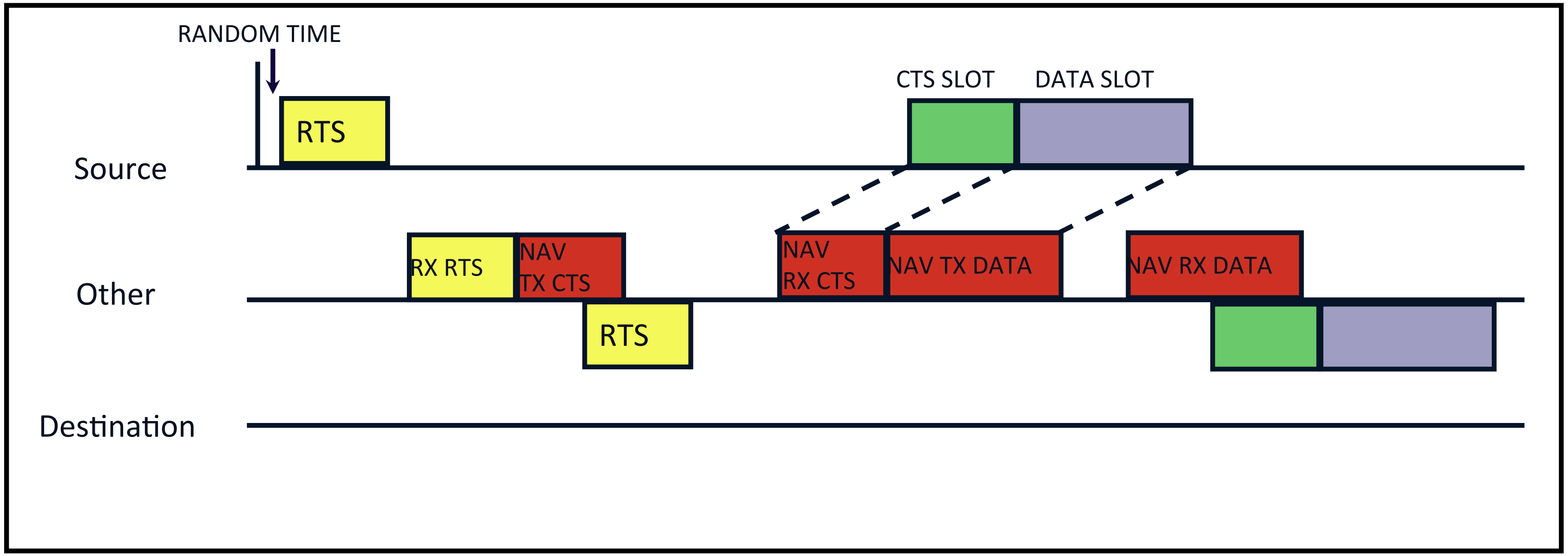

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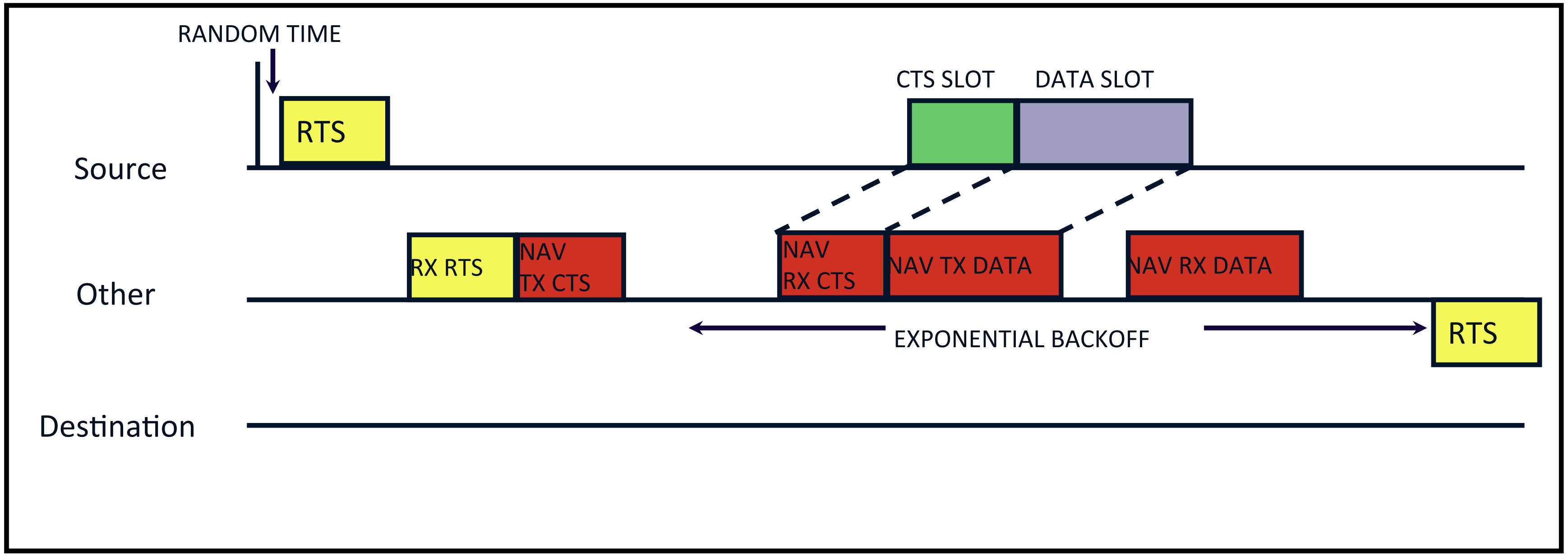

Performance evaluation (parameters)

New ns2-based simulation framework for performance comparison

- Shallow water scenario
- N static nodes randomly and uniformly scattered on the lower face of a cuboid L x L (base) x H, where H = 200m
- Single-hop and multi-hop with shortest path routing scenarios
- Different average nodal degrees (5, 10 and 15)
- Acoustic modem transmission range set to 1000m
- Poisson traffic process with different rate (low traffic up to high traffic)
- Three data rates: 2000bps, 8000bps and 28000bps
- Data packet size set to 2400 bits
- Physical header size set to 60 bytes

Performance evaluation (metrics of interest)

- Percentage of data packets sent
- Percentage of data packets received
- Percentage of data packets lost
- End-to-end latency
- Goodput

Performance evaluation (Results)

Single-hop (average degree 15 --> 16 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	ALOHA	SLOTTED ALOHA	APCAP	T-LOHI
100% Data delivery 2000bps						
100% Data delivery 28000bps						
more than 90% data delivery 2000bps						
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100% Data delivery 2000bps	$\lambda \le 0,25$	$\lambda \le 0,2$ no ACKs	-	-	-	-
		$\lambda \le 0,17$ ACKs	$\lambda \le 0,17$ ACKs	$\lambda \le 0,14$ ACKs		
100% Data delivery 28000bps						
more than 90% data delivery 2000bps						
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100% Data delivery 2000bps	λ ≤ 0,25	λ ≤ 0,2 no ACKs λ ≤ 0,17 ACKs	- λ ≤ 0,17 ACKs	- λ ≤ 0,14 ACKs	-	-
100% Data delivery 28000bps						
more than 90% data delivery 2000bps	λ ≤ 0,27	λ ≤ 0,25 no ACKs λ ≤ 0,21 ACKs	λ ≤ 0,19 no ACKs λ ≤ 0,23 ACKs	λ ≤ 0,07 no ACKs λ ≤ 0,18 ACKs	λ ≤ 0,04	λ ≤ 0,08
more than 90% data delivery 28000bps						

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28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	ALOHA	SLOTTED ALOHA	APCAP	T-LOHI
100% Data delivery 2000bps	λ ≤ 0,25	λ ≤ 0,2 no ACKs λ ≤ 0,17 ACKs	- λ ≤ 0,17 ACKs	- λ ≤ 0,14 ACKs	-	-
100% Data delivery 28000bps	λ ≤ 1	λ ≤ 0,5 no ACKs λ ≤ 0,27 ACKs	λ ≤ 0,03 no ACKs λ ≤ 1 ACKs	λ ≤ 0,03 no ACKs λ ≤ 0,35 ACKs	λ ≤ 0,06	λ ≤ 0,2
more than 90% data delivery 2000bps	λ ≤ 0,27	λ ≤ 0,25 no ACKs λ ≤ 0,21 ACKs	λ ≤ 0,19 no ACKs λ ≤ 0,23 ACKs	λ ≤ 0,07 no ACKs λ ≤ 0,18 ACKs	λ ≤ 0,04	λ ≤ 0,08
more than 90% data delivery 28000bps						

Performance evaluation (Results)

Single-hop (average degree 15 --> 16 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	ALOHA	SLOTTED ALOHA	APCAP	T-LOHI
100% Data delivery 2000bps	λ ≤ 0,25	λ ≤ 0,2 no ACKs λ ≤ 0,17 ACKs	- λ ≤ 0,17 ACKs	- λ ≤ 0,14 ACKs	-	-
100% Data delivery 28000bps	λ ≤ 1	λ ≤ 0,5 no ACKs λ ≤ 0,27 ACKs	λ ≤ 0,03 no ACKs λ ≤ 1 ACKs	λ ≤ 0,03 no ACKs λ ≤ 0,35 ACKs	λ ≤ 0,06	λ ≤ 0,2
more than 90% data delivery 2000bps	λ ≤ 0,27	λ ≤ 0,25 no ACKs λ ≤ 0,21 ACKs	λ ≤ 0,19 no ACKs λ ≤ 0,23 ACKs	λ ≤ 0,07 no ACKs λ ≤ 0,18 ACKs	λ ≤ 0,04	λ ≤ 0,08
more than 90% data delivery 28000bps	λ ≤ 1,2	λ ≤ 0,6 no ACKs λ ≤ 0,3 ACKs	λ ≤ 0,6 no ACKs λ ≤ 1,1 ACKs	λ ≤ 0,3 no ACKs λ ≤ 0,6 ACKs	λ ≤ 0,76	λ ≤ 0,5

Performance evaluation (Results)

Single-hop (average degree 15 --> 16 nodes in the network)

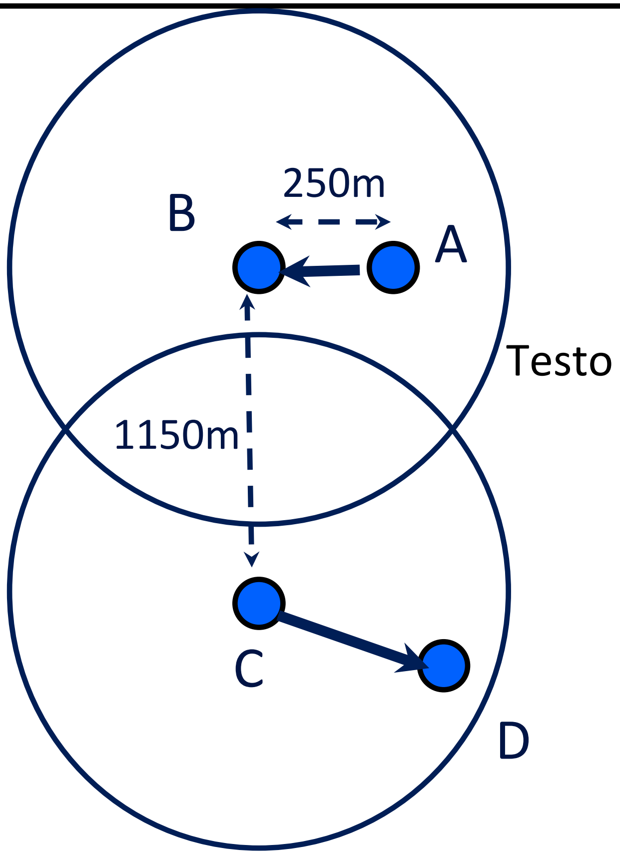
2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	ALOHA	SLOTTED ALOHA	APCAP	T-LOHI
100% Data delivery 2000bps	$\lambda \leq 0,25$	$\lambda \leq 0,2$ no ACKs $\lambda \leq 0,17$ ACKs	- $\lambda \leq 0,17$ ACKs	- $\lambda \leq 0,14$ ACKs	-	-
100% Data delivery 28000bps	$\lambda \leq 1$	$\lambda \leq 0,5$ no ACKs $\lambda \leq 0,27$ ACKs	$\lambda \leq 0,03$ no ACKs $\lambda \leq 1$ ACKs	$\lambda \leq 0,03$ no ACKs $\lambda \leq 0,35$ ACKs	$\lambda \leq 0,06$	$\lambda \leq 0,2$
more than 90% data delivery 2000bps	$\lambda \leq 0,27$	$\lambda \leq 0,25$ no ACKs $\lambda \leq 0,21$ ACKs	$\lambda \leq 0,19$ no ACKs $\lambda \leq 0,23$ ACKs	$\lambda \leq 0,07$ no ACKs $\lambda \leq 0,18$ ACKs	$\lambda \leq 0,04$	$\lambda \leq 0,08$
more than 90% data delivery 28000bps	$\lambda \leq 1,2$	$\lambda \leq 0,6$ no ACKs $\lambda \leq 0,3$ ACKs	$\lambda \leq 0,6$ no ACKs $\lambda \leq 1,1$ ACKs	$\lambda \leq 0,3$ no ACKs $\lambda \leq 0,6$ ACKs	$\lambda \leq 0,76$	$\lambda \leq 0,5$

Multi-hop scenarios

Effects of physical level interference

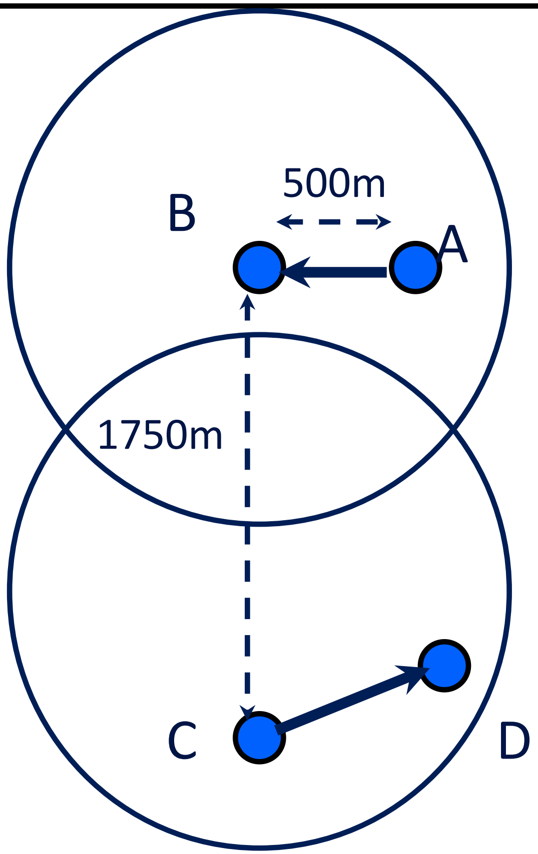


A is sending data to B
C is sending data to D
d(A,B) = 250m
d(C,B) ≤ 1150m

If while B is receiving the packet from A, it is reached by the signal transmitted by C, both packets have to be discarded

Multi-hop scenarios

Effects of physical level interference

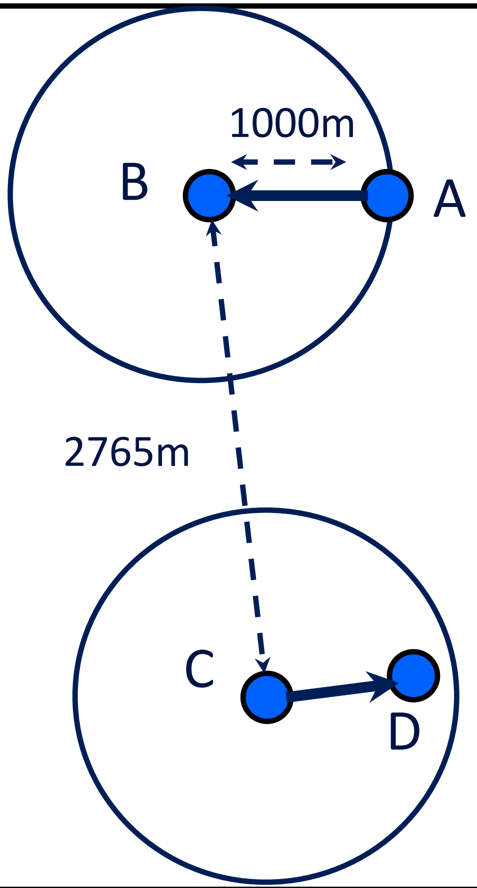


A is sending data to B
C is sending data to D
d(A,B) = 500m
d(C,B) ≤ 1750m

If while B is receiving the packet from A, it is reached by the signal transmitted by C, both packets have to be discarded

Multi-hop scenarios

Effects of physical level interference



A is sending data to B
C is sending data to D
d(A,B) = 1000m
d(C,B) ≤ 2765m

If while B is receiving the packet from A, it is reached by the signal transmitted by C, both packets have to be discarded

Performance evaluation (Results)

Multi-hop (average degree 15 --> 100 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	ALOHA	SLOTTED ALOHA	APCAP
100% Data delivery 2000bps	-	-	-	-	-
		-	$\lambda \leq 0,05$ ACKs	$\lambda \leq 0,05$ ACKs	
100% Data delivery 28000bps					
more than 90% data delivery 2000bps					
more than 90% data delivery 28000bps					

Performance evaluation (Results)

Multi-hop (average degree 15 --> 100 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	ALOHA	SLOTTED ALOHA	APCAP
100% Data delivery 2000bps	-	- -	- $\lambda \le 0{,}05$ ACKs	- $\lambda \le 0{,}05$ ACKs	-
100% Data delivery 28000bps					
more than 90% data delivery 2000bps	-	- -	- $\lambda \le 0{,}075$ ACKs	- $\lambda \le 0{,}08$ ACKs	-
more than 90% data delivery 28000bps					

Performance evaluation (Results)

Multi-hop (average degree 15 --> 100 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	ALOHA	SLOTTED ALOHA	APCAP
100% Data delivery 2000bps	-	- -	- $\lambda \leq$ 0,05 ACKs	- $\lambda \leq$ 0,05 ACKs	-
100% Data delivery 28000bps	-	- $\lambda \leq$ 0,07 ACKs	- $\lambda \leq$ 0,33 ACKs	- $\lambda \leq$ 0,33 ACKs	-
more than 90% data delivery 2000bps	-	- -	- $\lambda \leq$ 0,075 ACKs	- $\lambda \leq$ 0,08 ACKs	-
more than 90% data delivery 28000bps					

Performance evaluation (Results)

Multi-hop (average degree 15 --> 100 nodes in the network)

2000bps (transmission delay is twice the maximum propagation delay)

28000bps (transmission delay is 1/6 the maximum propagation delay)

	PDAP	DACAP	ALOHA	SLOTTED ALOHA	APCAP
100% Data delivery 2000bps	-	- -	- $\lambda \leq 0{,}05$ ACKs	- $\lambda \leq 0{,}05$ ACKs	-
100% Data delivery 28000bps	-	- $\lambda \leq 0{,}07$ ACKs	- $\lambda \leq 0{,}33$ ACKs	- $\lambda \leq 0{,}33$ ACKs	-
more than 90% data delivery 2000bps	-	- -	- $\lambda \leq 0{,}075$ ACKs	- $\lambda \leq 0{,}08$ ACKs	-
more than 90% data delivery 28000bps	$\lambda \leq 0{,}13$	$\lambda \leq 0{,}11$ no ACKs $\lambda \leq 0{,}11$ ACKs	$\lambda \leq 0{,}13$ no ACKs $\lambda \leq 0{,}33$ ACKs	$\lambda \leq 0{,}13$ no ACKs $\lambda \leq 0{,}33$ ACKs	$\lambda \leq 0{,}12$

Conclusioni

Rispetto ai protocolli per reti radio, in ambito UASNs le differenti problematiche assumono differenti priorità.

- Il delay può essere considerato un requisito meno stringente rispetto alle reti wireless di comunicazione
- Una grande cura deve essere dedicata alla gestione delle collisioni (tenendo presente che il rapporto tra i tempi di propagazione e i tempi di trasmissione è ben maggiore che nel caso di reti radio)
- I protocolli devono essere adattivi per poter operare in differenti condizioni rispetto a: propagazione delle onde, dimensione dalla rete, range trasmissivi, densità dei nodi, intensità del traffico.
- Node placement and mobility planning