HOCHSCHULE
HANNOVER
UNIVERSITY OF
APPLIED SCIENCES
AND ARTS
–
*Fakultät IV
Wirtschaft und
Informatik*

Fahrzeugvernetzung – V2X

Lecture 4: Medium Access Control Protocols

Hugues Tchouankem, 20.10.2021

Lecture 4
Previous Lecture

- **Geographic Networking (GeoNetworking)**
  - *GeoNetworking Beaconing*
- **Addressing Methods**
  - *GeoUnicast, GeoAnyCast, GeoBroadcast,*
  - *Single-Hop Broadcast, Topological Scoped Broadcast (TSB)*
- **Forwarding Algorithms**
  - *Greedy Forwarding (GF) algorithm*
  - *Contention-based Forwarding (CBF) algorithm*
- **Location Service**
  - *Reactive Location Service (RLS)*
  - *Simple Location Service (SLS)*
- **Duplicate Packet Detection Technique**

Lecture 4
Outline

- ► Multiple Access Approaches
- ► Random Access Protocols
- ► Reservation-based Access Protocols
- ► Carrier Sense Multiple Access
- ► Hidden/Exposed Terminal Problem
- ► TDMA-based MAC Protocols for V2X

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Coordination of Access to Communication Medium

- How to **coordinate the access** of **multiple sending** and **receiving** stations to a **shared** broadcast channel?
- Consider a **classroom** where a **teacher** and **students** share the same, single, broadcast medium. A central problem is that of determining **who** gets to talk (that is, transmit into the channel), and **when**
  - We have to elaborate a set of protocols for sharing the broadcast channel:
    - *“Raise your hand if you have a question”*
    - *“Don’t monopolize the conversation”*
    - *“Don’t interrupt when someone is speaking”*
- Computer networks similarly have protocols - so-called **multiple access protocols** - by which stations **regulate their transmissions** into the shared broadcast channel

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Multiple Access Approaches (1/2)

- **Characteristics:**
  - **Shared medium**: All stations share the same communication channel
  - **Broadcast medium**: All stations within a transmission range of sender receive the signal

- **Challenges:**
  - Often **no centralized control** and **uncoordinated** channel access
  - A sender **cannot block access** to the channel by others
  - If more than **two stations** transmit at the same time **collisions may occur** at all of the receivers

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Multiple Access Approaches (2/2)

- **Static allocation** of sub-channel:
  - Channel capacity is **divided** among the stations
  - **Frequency, time, or code** is reserved for each station
  - **No further control** of channel access is needed
  - Provide well-defined **quality of service** (latency, throughput, etc.)

- **Dynamic assignment** of the channel
  - **No a priori allocation** – Before sending stations have to **obtain permission** to send
  - Access procedure can have **centralized** control or it can be **decentralized**

- **Random access**
  - **No a priori allocation** – No coordination of/among stations
  - **Collisions** are inevitable – But have to be detected and fixed

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Medium Access Control (MAC) Protocols

- Medium access control protocols are needed – Which approach to choose?
  - Centralized vs. distributed
  - Deterministic vs. stochastic
  - **Challenge: Coordination among stations (Who? When?)**

- MAC protocol is responsible for **regulating access** to the **shared communication medium** by scheduling transmissions in
  - Time - TDMA
  - Frequency - FDMA
  - Space - SDMA
  - Unique codes - CDMA

  to distinguish different users

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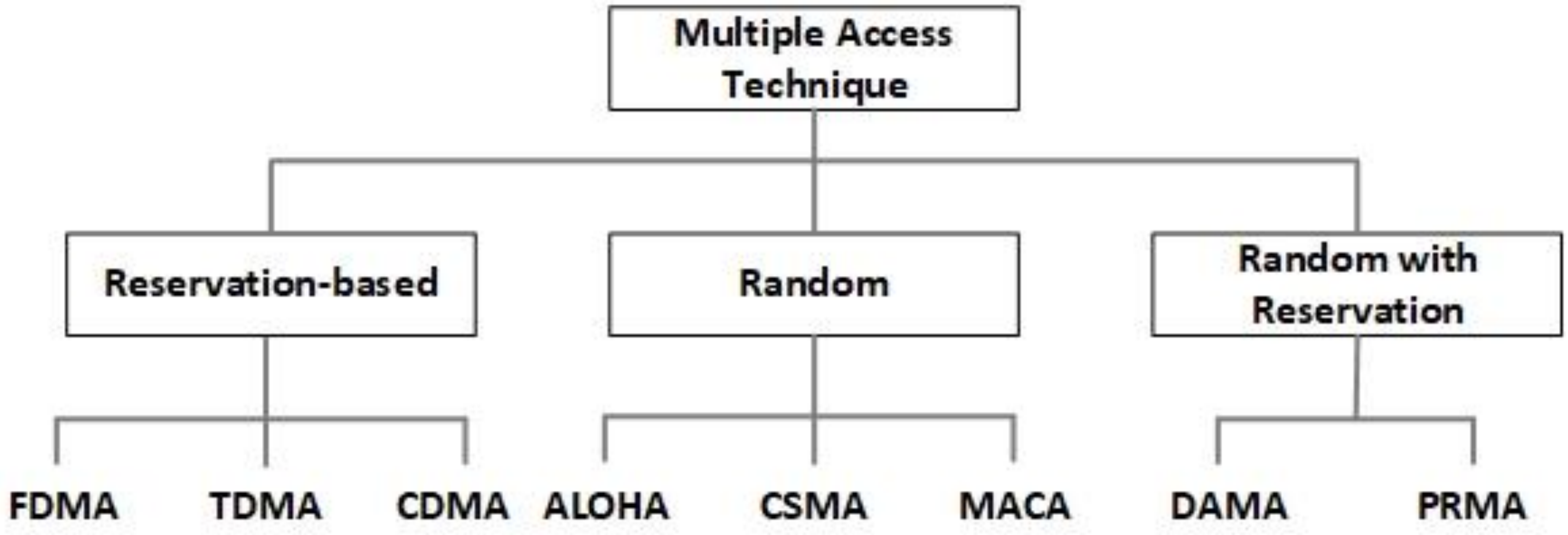
Classification of Wireless MAC Protocols

- Three main categories of MAC protocols for **wireless networks**:
  - **Reservation-based**: Static allocation or dynamic assignment of resources to stations
  - **Random access**: Stations compete for the channel using randomized procedures - No collision free allocation
  - **Random with reservation:** Stations compete using **random access** to obtain a dynamic assignment of resources



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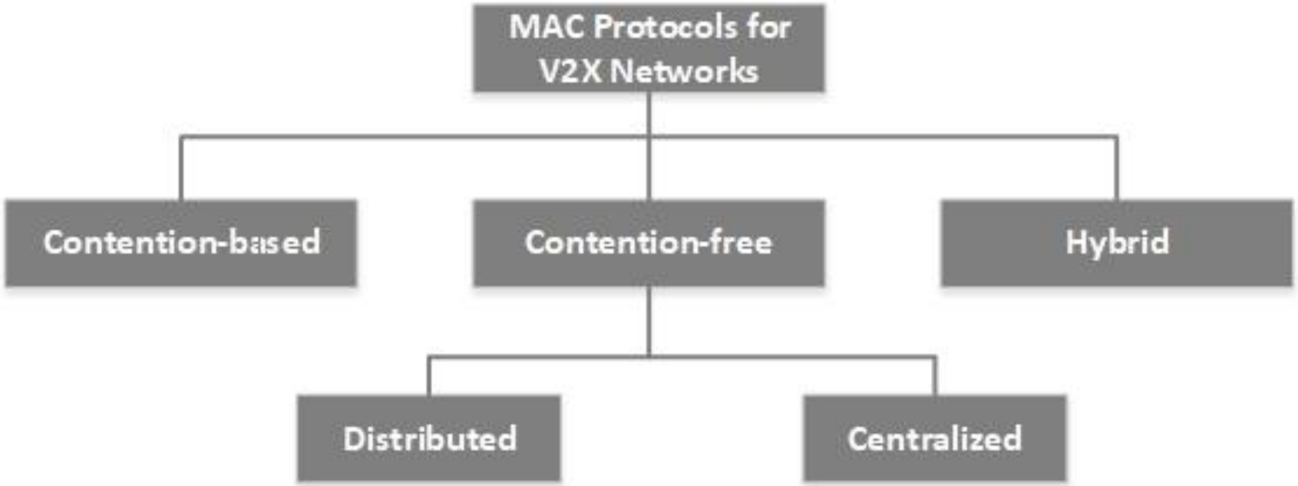
MAC Protocols for V2X

- Three main categories of MAC protocols for **V2X networks:**
  - **Contention-based**: No predetermined schedule and vehicles are allow to access the channel randomly when they need to transmit – Collisions may occur
  - **Contention-free**: Requires a predetermined channel access schedule. Each vehicle is allow to access the channel by a predetermined time slot, frequency band or code sequence
    - No message collisions between vehicles in the **same** two-hop neighborhood
  - **Hybrid:** Combine contention-based and contention-free to provide a high QoS and reduce the collision probability



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Requirements on MAC Layer for V2X-Networks

- **Self-organizing**: Scheduling of transmissions have to be performed in a distributed manner
- **Reactiveness**: Management of allocated resources should be flexible and fast enough to let the protocol react timely to topology changes due to mobility

- **Scalability**: Number of stations participating in the network is **unknown a priori**. This number is expected to grow to several hundreds of stations that are within radio range of each other
  - MAC protocol should be non-blocking such that new vehicles can always transmit

- **Mitigation of hidden terminal situations**: Hidden terminal problem is present in V2X networks regardless of MAC method
  - For each MAC protocol it is necessary to evaluate the **impact of hidden terminals** in terms of performance degradations

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Requirements on MAC Layer for Road Traffic Safety Applications

- **Delay:** Road traffic safety applications require a **predictable channel access** such that the maximum channel access delay is upper-bounded
  - Real-time deadlines can be supported

- **Reliability:** MAC protocol should schedule transmissions to minimize interference between stations
  - Minimize **interference** between transmitters to maximize the **packet reception probability** for the **closest neighboring** stations is desirable

- **Fairness:** All the stations should be able to access the channel with **equal probability** within a limited time period, e.g. the CAM update frequency
  - This can be enforced by a predictable MAC method

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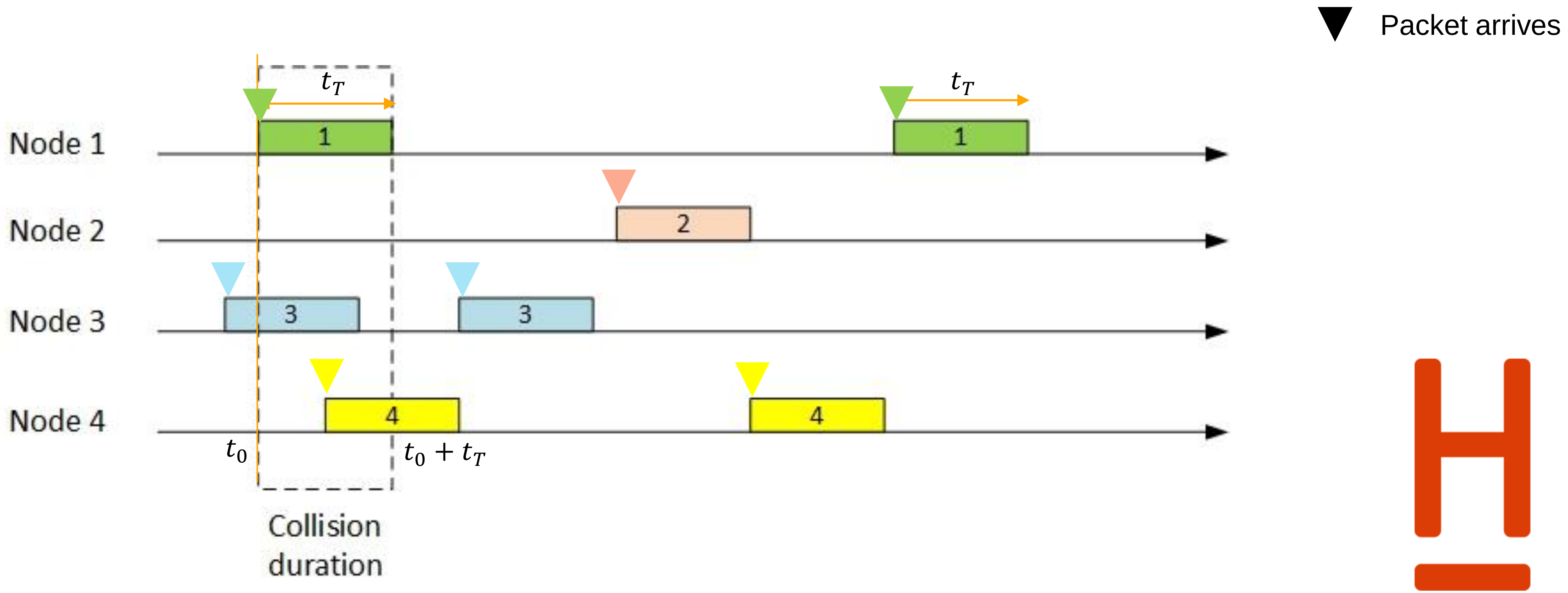
Pure ALOHA Protocol

- ► An unslotted **fully decentralized** protocol
- ► Whenever a station has a packet to send, it **simply transmits** the packet
  - ► If collision occurs, it waits for **a random period** of time and re-sends it again



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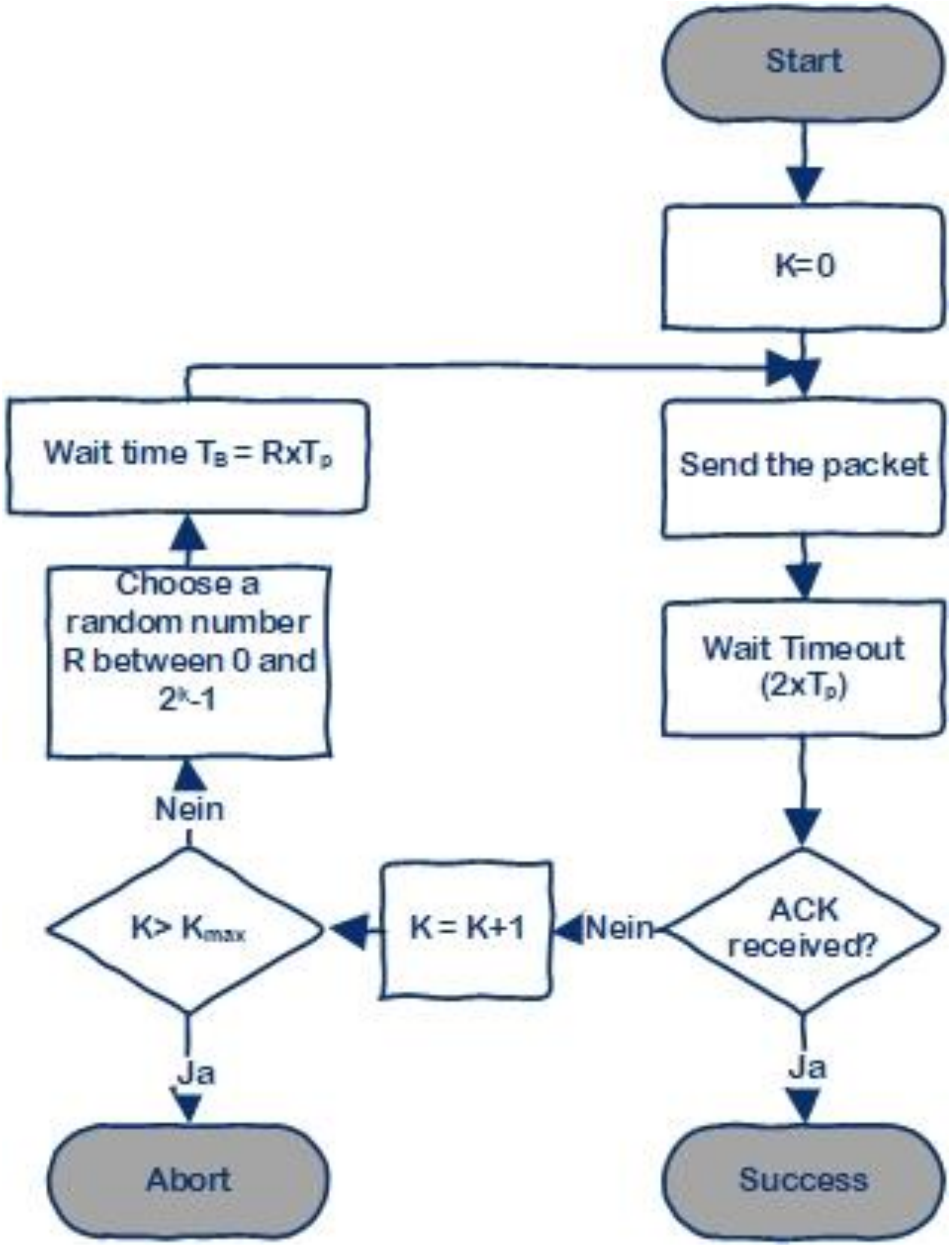
Procedure for pure ALOHA

- ► K is the number of attempts, K_{max} is 15
- ► T_p is the maximum propagation time



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Derivation of Efficiency of pure ALOHA

- Suppose there are N stations
- Assume all stations use packets with transmission duration t_T
- Assume that each station always has a packet to send and that the station transmits with **probability p** for a fresh packet as well as for a packet retransmission
- Probability that all other stations do not begin a transmission in the interval $[t_0 - t_T, t_0]$ is $(\mathbf{1}-\mathbf{p})^{\boldsymbol{N}-\mathbf{1}}$
- Probability that all other stations do not begin a transmission in the interval $[t_0, t_0 + t_T]$ is also $(\mathbf{1}-\mathbf{p})^{\boldsymbol{N}-\mathbf{1}}$
- Probability that **a given station has a successful** transmission

$$\mathbf{p}(\mathbf{1}-\boldsymbol{p})^{\boldsymbol{N}-\mathbf{1}}(\mathbf{1}-\boldsymbol{p})^{\boldsymbol{N}-\mathbf{1}} = \mathbf{p}(\mathbf{1}-\mathbf{p})^{\mathbf{2}(\boldsymbol{N}-\mathbf{1})}$$

- Efficiency: Probability that any one of the **N stations** has a success (Transmission without collision)

$$\boldsymbol{E}(\boldsymbol{p}) = \boldsymbol{N}\mathbf{p}(\mathbf{1}-\mathbf{p})^{\mathbf{2}(\boldsymbol{N}-\mathbf{1})}$$

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Maximum Efficiency of pure ALOHA

- **Efficiency**: Probability that any one of the N stations has a success $\boldsymbol{E(p)} = \ \boldsymbol{N}\mathbf{p}(\mathbf{1}-\mathbf{p})^{\ \mathbf{2(N-1)}}$
- Maximum efficiency $\boldsymbol{E}_{\mathbf{max}}$ → Find the $\boldsymbol{p}^*$ that maximizes the efficiency for a large number of stations $N \to \ \infty$

$$\frac{dE(p)}{dp} = 0 \xrightarrow{\text{yields}} N(1-p^*)^{\ 2(N-1)} - Np^*2(N-1)\ (1-p^*)^{\ 2(N-1)-1} = 0$$

$$N(1-p^*)^{\ 2(N-1)-1}\big((1-p^*) - p^*2(N-1)\big) = 0$$

$$p^* = \frac{1}{2N\ -1} \to \boldsymbol{E}_{\mathbf{max}} = \frac{\boldsymbol{N}}{\mathbf{2}\boldsymbol{N}-\mathbf{1}}(\mathbf{1} - \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{N}-\mathbf{1}})^{\ \mathbf{2(N-1)}}$$

$$\lim_{N\to\infty}(1-\frac{1}{N})^{\ N} = 1/e$$

$$\lim_{N\to\infty} E_{\max} = \lim_{N\to\infty}\frac{N}{2N-1}(1-\frac{1}{2N-1})^{\ 2(N-1)}$$

$$\lim_{N\to\infty}\frac{N}{2N-1}\frac{\left(1-\frac{1}{2N-1}\right)^{2N-1}}{\left(1-\frac{1}{2N-1}\right)} = \frac{1}{2}\cdot\frac{1}{e} = \mathbf{0.184}$$

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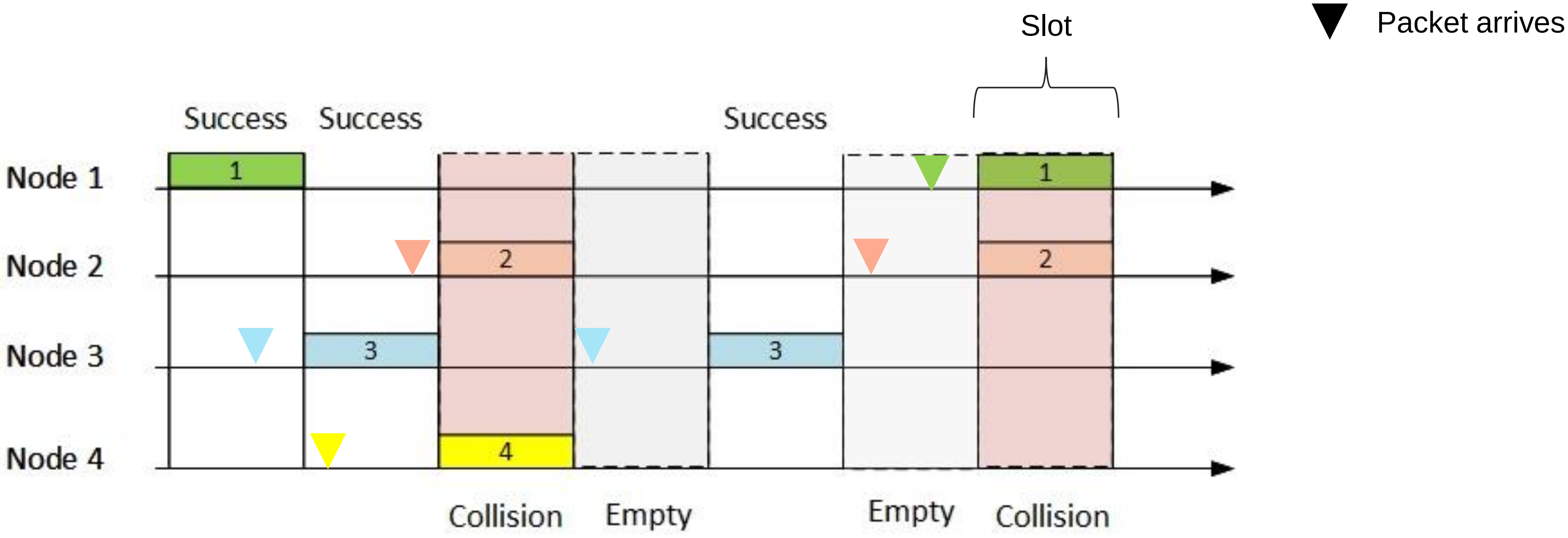
Slotted ALOHA Protocol

- An slotted, fully decentralized protocol
- Time is divided into **slots of fixed size**
- When the station has a fresh packet to send, it **waits until the beginning of the next slot** and transmits the entire packet in the slot



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Derivation of efficiency of slotted ALOHA

► Suppose there are **N stations**

► Assume that each station always has a packet to send and that the station transmits with **probability** $\mathbf{p}$ for a fresh packet as well as for a packet retransmission

► Probability that a given station transmits is $\mathbf{p}$

► Probability that the **remaining stations do not transmit** is $(\mathbf{1}-\boldsymbol{p})^{\boldsymbol{N}-\mathbf{1}}$

► Probability that **a given station** has a **successful transmission**

$$\mathbf{p}(\mathbf{1}-\boldsymbol{p})^{\boldsymbol{N}-\mathbf{1}}$$

► Efficiency: Probability that **any one of the N stations** has a success (Transmission without collision)

$$\boldsymbol{E}(\boldsymbol{p})=\boldsymbol{N}\mathbf{p}(\mathbf{1}-\mathbf{p})^{\boldsymbol{N}-\mathbf{1}}$$

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Maximum Efficiency of slotted ALOHA

► **Efficiency:** Probability that any station of the N stations has a success

$$\boldsymbol{E(p) = N\mathbf{p}(1-\mathbf{p})^{N-1}}$$

► **Maximum efficiency $\boldsymbol{E_{\max}}$** → Find the $\boldsymbol{p}^*$ that maximizes this efficiency for a large number of nodes

$$\frac{dE(p)}{dp} = 0 \rightarrow N(1-p^*)^{N-1} - Np^*(N-1)(1-p^*)^{N-2} = 0$$

$$N(1-p^*)^{N-2}\big((1-p^*) - p^*(N-1)\big) = 0$$

$$p^* = \frac{1}{N} \Rightarrow \boldsymbol{E_{\max} = (1-\frac{1}{N})^{N-1}}$$

$$\lim_{N\to\infty}(1-\frac{1}{N})^{N} = 1/e$$

$$\lim_{N\to\infty} E_{\max} = \lim_{N\to\infty}(1-\frac{1}{N})^{N-1}$$

$$\lim_{N\to\infty}\frac{\left(1-\frac{1}{N}\right)^{N}}{\left(1-\frac{1}{N}\right)} = \frac{1}{e} \approx \mathbf{0.37}$$

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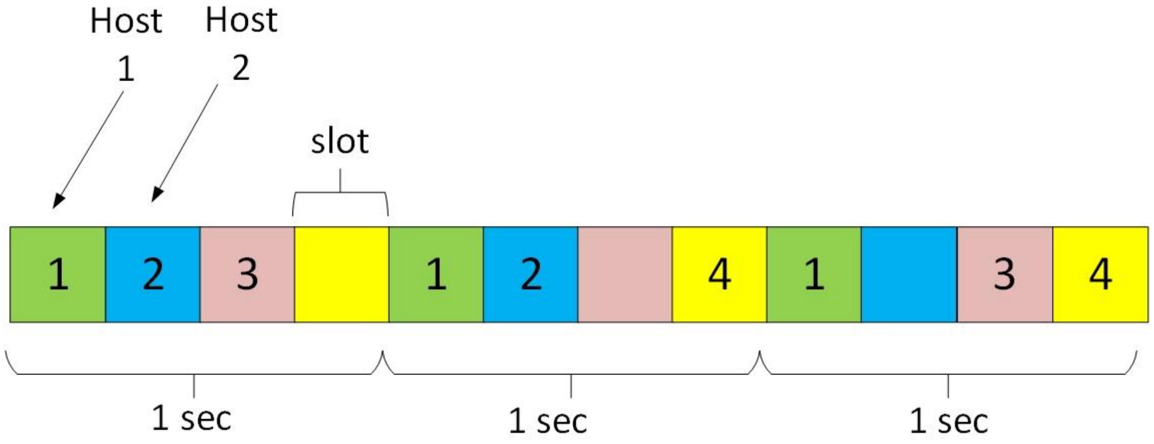
Time Division Multiple Access (TDMA)

- Divide channel into rounds of **n time slots** each
  - Assign **different stations** to **different time slots** within a round
  - Unused time slots are idle
  - Used in GSM cell phones & digital cordless phones
  - Robust against **frequency shifts**

  - Scenario with 1-second rounds, 4 timeslots (250ms each) per round



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Time Division Multiple Access (TDMA)

- TDMA systems can easily **assign the channel dynamically**
  - Centralized control required
  - Stations need to obtain permission to send
  - Base station give permission to send to a station
  - Base station is a single point of failure

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TDMA Limitations

- A station is limited to **an average rate** even when it is **the only** station with packets to send
  - A station must **always wait for its turn** in the transmission sequence even when it is the **only station** with a frame to send
- Receiver has to **synchronize precisely**
- Overhead for keeping **tight time synchronization** among all stations

- Synchronization issue specific to V2X-Networks
  - Transmission times must be **perfectly synchronized** to ensure that packets are received in the **correct time slot** and do not cause interference
  - Each time slot must have **a guard time**, which reduces the interference probability, but **decreases the spectral efficiency**

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Frequency Division Multiple Access (FDMA)

- Divide the channel into **different frequencies**
  - Assign **each frequency to one** of the stations
- It avoids **collisions** and divides the bandwidth fairly among the nodes
- Fixed frequency allocation
  - Permanent, e.g. radio broadcast
  - Frequency hopping, e.g. GSM, Bluetooth

- FDMA shares both the advantages and drawbacks of TDMA
  - **Simple** to implement, **no time synchronization** needed

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FDMA Limitations

- A station has a limited bandwidth even when it is the only station with packets to send
- **Receiver** has to have a precise **bandpassfilter**
- **Guard bands** between individual frequency bands needed

- **Frequency shifts** are specific to V2X-Networks
  - Due to the unpredictable **Doppler shift** of the signal spectrum because of user mobility, a guard band between adjacent channels must be added
    - **Guard bands** will reduce the probability that adjacent channels will interfere, but **decrease the utilization of the spectrum**

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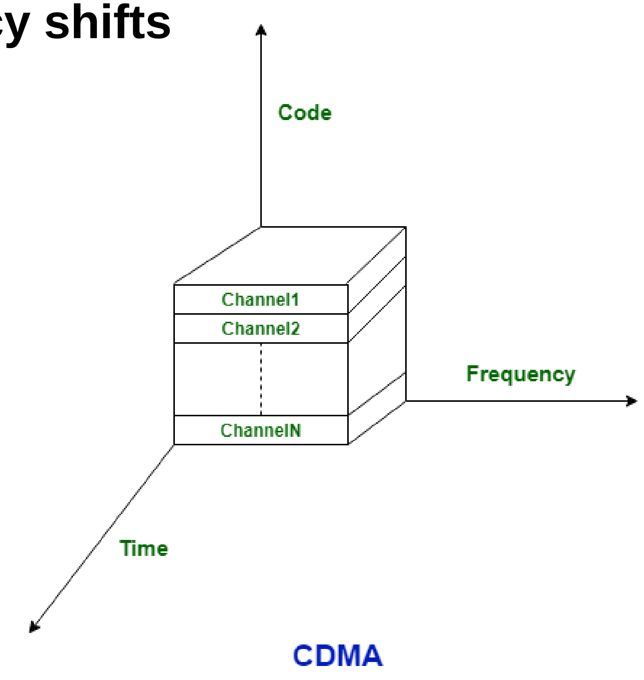
Code Division Multiple Access (CDMA)

- Assign **a different code** to **each station**
  - Each station uses its unique code to encode the data bits it sends
- Different stations can transmit **simultaneously** assuming the receiver **knows** the sender's **code**
- Robustness against **time and frequency shifts**



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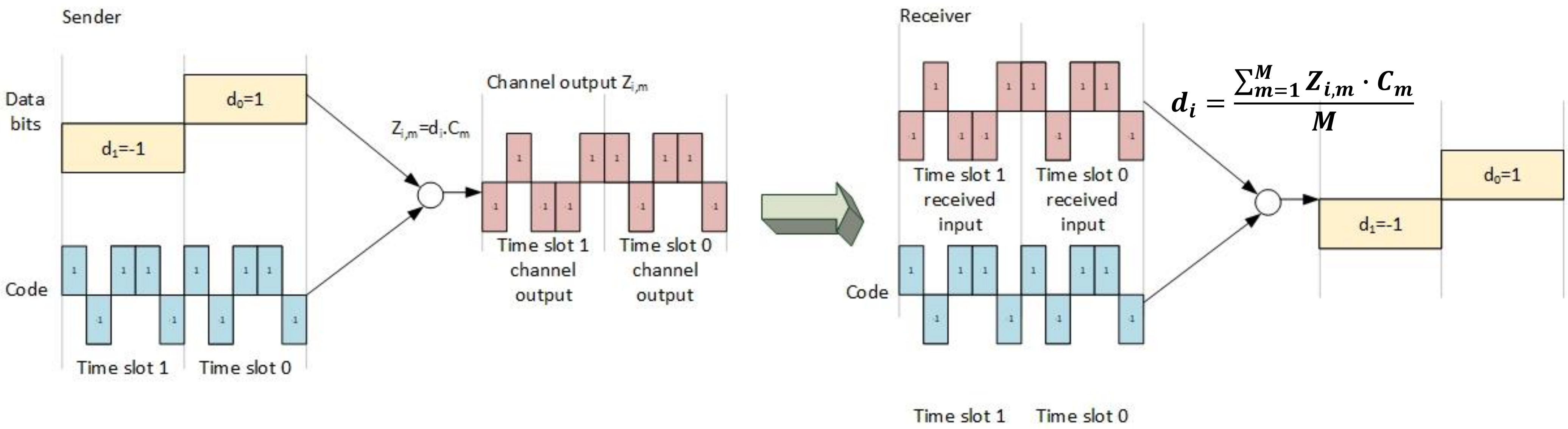
CDMA Encoding

► Each bit being sent is encoded by multiplying it by a signal (the code) that changes at a much faster rate than the original sequence of data bits



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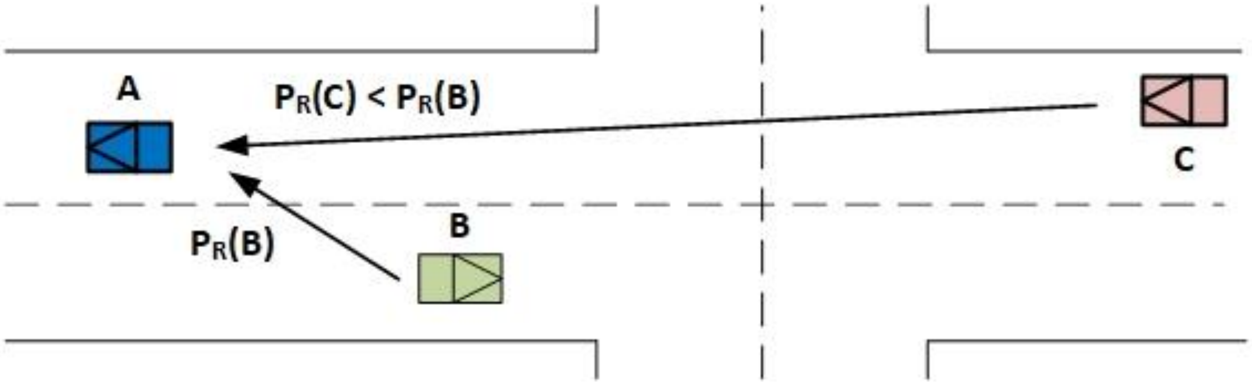
CDMA Limitations

- ► All signals **have** to arrive at a **receiver with roughly the same power level**
  - ► **Closed-loop power control**: A dedicated channel is needed to continuously give feedback to **participating users** on how much their **transmit power should be**
- ► **Near-Far Effect**: Vehicles A, B and C share the same frequency band and their signals are separable at the vehicle A by their unique code
- ► Received power of B at a particular time instant might be much greater than that from C
  - ► If power control is not applied, **the signal of B will overpower the signal of C** at the vehicle A



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Comparison of Reservation-based MAC Protocols

	TDMA	FDMA	CDMA
Idea	Time is slotted, static or dynamic time slot allocation	Frequency is segmented into sub-bands	Spread spectrum with orthogonal codes
Stations	Stations are active for short disjoint periods of time on the same frequency	Each station has its own frequency band and is not interrupted	All stations can be active at the same time on the same frequency
Signal separation	Synchronization in time domain	Bandpass filtering in frequency domain	Matched filter in code domain
Advantages	Flexible, can assign time slots on demand	Simple, robust	Flexible, other codes only add noise
Disadvantages	Synchronization is difficult, guard times needed	Inflexible, frequency is scarce	Complex receivers, need sophisticated power control

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Carrier Sense Multiple Access (CSMA)

- The CSMA/CA is a **random contention-based access mechanism** following the principle of ***listen before talk*** called ***carrier sensing***
  - A station listens to the channel before transmitting, i.e., **the channel is only accessed if it is sensed to be idle**
- Goal is to **minimize the interference** in the system → Increase the packet reception probability

- When the physical layer observes no activities on it
  - A station then waits **a random back-off time** chosen from the interval [0,CW]
  - CW is known as the **contention window size** and is **decremented** as the medium is idle
  - Whenever the **countdown reaches zero**, the frame is **immediately transmitted**

CW: Contention Window

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CSMA Back-off Procedure

► Back-off procedure works as follows:

1) Draw an **integer** from a **uniform distribution** [0, CW]
2) Multiply this integer with the **slot time**, T_{slot}, derived from the PHY layer in use (T_{slot} =13 µs), and set this as the **back-off value**
3) Decrease the back-off value by **one T_{slot} for every T_{slot}** the channel is sensed as free
4) Upon reaching **a back-off value of 0**, transmit directly

CW: Contention Window

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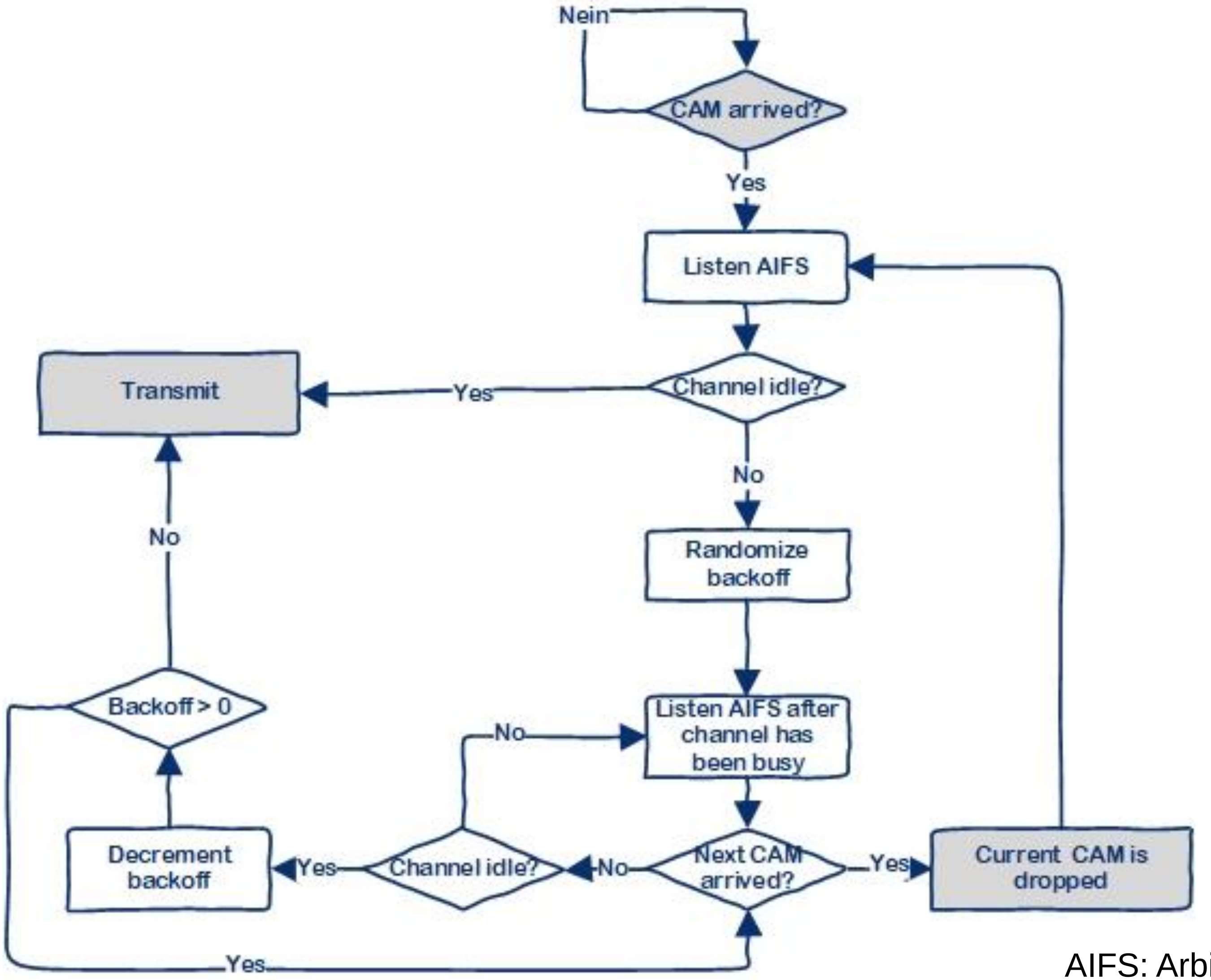
Procedure of CSMA when broadcasting CAMs



AIFS: Arbitration Interframe Spacing

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Quality of Service (QoS) for IEEE802.11p

- 802.11p MAC supports QoS
  - Dividing the data traffic into **four different queues** called access categories (AC)
  - Highest priority queue has the shortest T_{AIFS} and the smallest initial CW

Priority	Traffic Type	AC	T_{AIFS} [µs]	CW_{min}	CW_{max}
Highest	Voice	AC_VO	58	3	7
	Video	AC_VI	71	7	15
	Best Effort	AC_BE	110	15	1023
Lowest	Background	AC_BK	149	15	1023

AIFS: Arbitration Interframe Spacing
CW: Contention Window

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CSMA for Unicast Transmissions

- In **unicast transmissions**, the receiver transmits a receipt also known as **acknowledged (ACK)** upon **successful** reception

- During high network utilization periods ACKs can be lost due to **simultaneous transmissions caused by hidden nodes** or wireless **channel impairments** such as **fading**

- For every attempt to transmit a specific packet (where the ACK from the receiver is repeatedly missing), the station **doubles the CW**, resulting in a greater spread of simultaneous transmission attempts during high utilization periods
- BUT the **reliability** comes at the **expense of a random delay** which is not upper bounded

- Due to the **lack of ACK** in **broadcast communication**, CW in V2X is always set to its CW_{min} (**CW will never be doubled no matter what the network condition is**)

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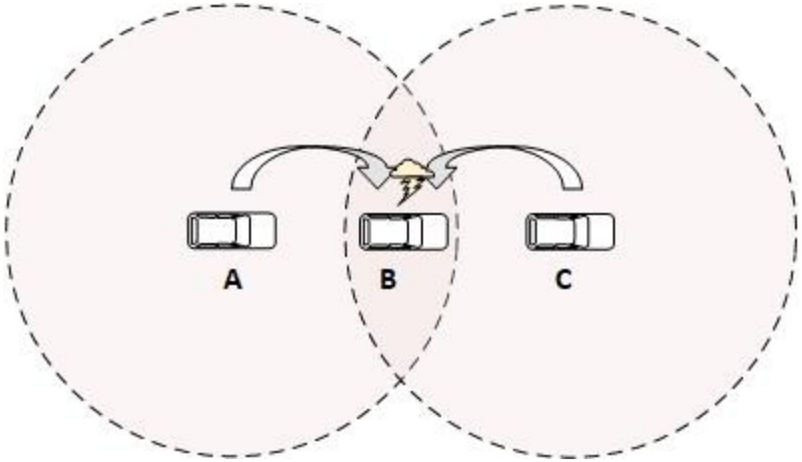
Hidden Terminal Problem (1/2)

- ► Hidden terminal problem is one of the **performance limiting factor** in V2X Networks
- ► In other centralized networks, where TDMA or CDMA are used, the AP/BS controls channel access and the hidden terminal problem does not exist
- ► A is hidden from C and C is hidden from A
  - ► A senses free medium and starts sending to B
  - ► C cannot hear A
  - ► C senses free medium and starts sending to B
  - ► A cannot hear C
  - → Leading to a **packet collision** at B



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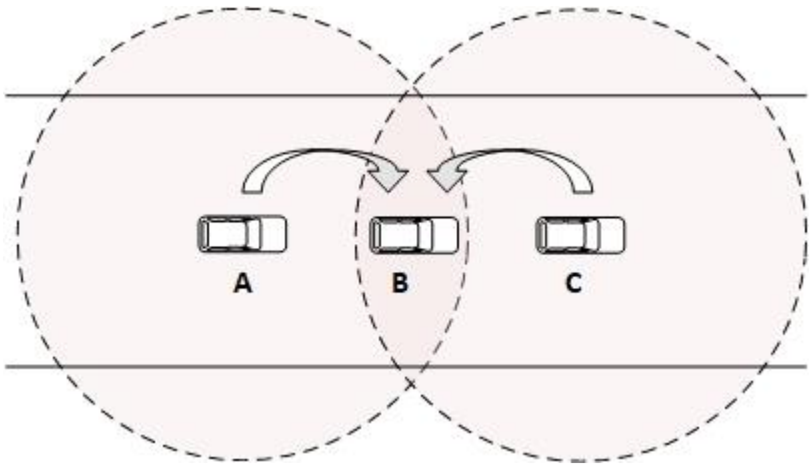
Hidden Terminal Problem (2/2)

- Can be combatted by preceding every transmission with control packets
  - Request-to-send (**RTS**) and clear-to-send (**CTS**) used to notify all stations in the network about an **upcoming transmission**

- Not feasible in V2X networks due to the **broadcast nature** of the data traffic, implying more than **one intended receiver**



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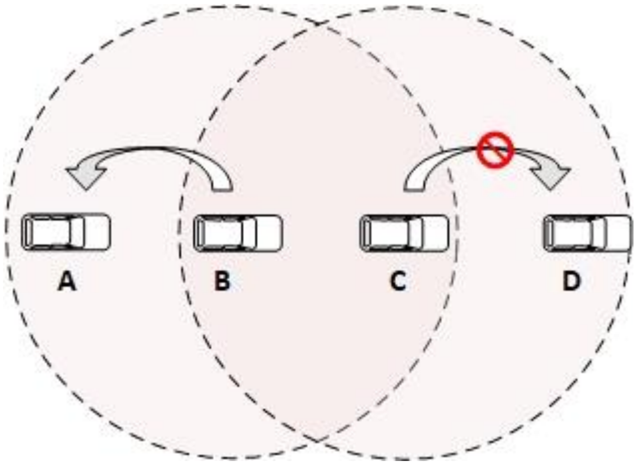
Exposed Terminal Problem (2/2)

- ► C is exposed to the transmission of B
  - ► B senses free medium and starts sending to A
  - ► C want to transmit data to D
  - ► C could transmit to D without causing a collision
    - ► Neither at receiver A nor at receiver D

  → C senses busy medium and **does not start sending to D**



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AdHoc MAC

- Distributed **TDMA-based MAC** protocol
  - It is contention-free MAC protocol which implements a **dynamic TDMA mechanism** that is able to provide prompt access based on distributed access technique
- **Vehicles are grouped** into a **set of clusters** with no cluster head
- Each cluster contains a restricted number of vehicles that are one-hop away
- Vehicles broadcast the **status of time slots used** by all the other vehicles within its one-hop neighborhood
- Upon receiving the status information, **each vehicle knows the time slots used by all of the vehicles within its two-hop** neighborhood and the set of accessible time slots
- Vehicles **randomly select the free time slot** to transmit its data without causing any packet collisions

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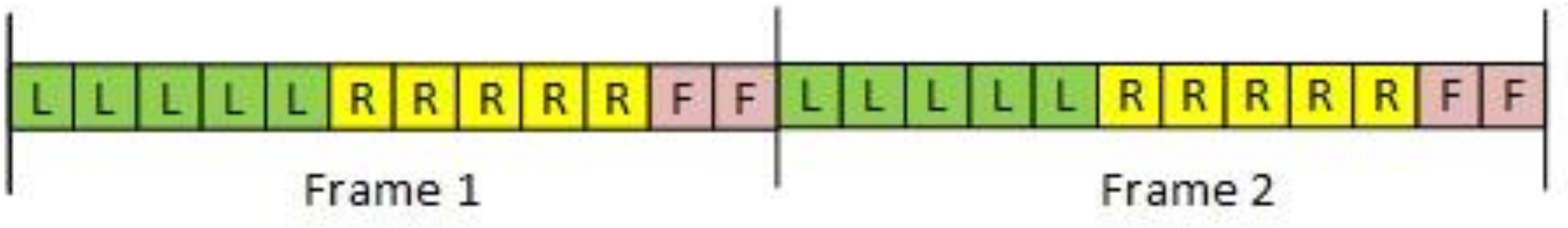
Vehicular MAC (VeMAC)

- ► Distributed multi-channel **TDMA-based MAC** protocol
  - ► It is contention free MAC protocol
- ► In the **control channel**, the vehicle exchanges the **status information of time slots** with its one-hop neighbors
- ► Each vehicle determines **its time slot in the service channel** and achieves contention-free accessing channel
- ► Time slots is allocated to the vehicle **based on their direction on the road**
  - ► L and R group of time slots are allocated to left and right direction vehicles respectively, and time slots of F is allocated to RSU



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Unified TDMA-based Scheduling Protocol (UTSP)

- ► Contention-free centralized **TDMA-based MAC** protocol
- ► **Roadside units (RSU)** collect the information of the vehicles within its communication range
- ► RSU **decides how to allocate the time slots to the vehicles** for their data transmission requests based on **a weight-factor-based scheduler**
- ► Weight factor takes into consideration the **channel quality** of communication links**,** the **speed** based fairness among vehicles**,** and different **access categories**
- ► Interference problem can occur between vehicles in the **overlapping regions** where several RSUs are used to coordinate access to the channel

Lecture 4
Adaptive Collision-Free MAC (ACFM)

- ► Contention-free centralized **TDMA-based MAC** protocol based on **a dynamic time slot reservation mechanism in Roadside Units (RSUs)**
- ► Time is divided into frames and **each frame is divided into a fixed number of time slots**
  - ► 1 RSU Slot (RS) which is used by an RSU **to broadcast control messages** to the vehicles within its coverage area
  - ► 36 Data Slots (DS) which can be used by the vehicles to broadcast CAMs to their neighboring vehicles
  - ► Control message that is periodically diffused by an RSU contains the **DS assignment schedule for vehicles under its coverage**
- ► Due to high node mobility, the interval of time in which the vehicle stays in an RSU region is very short → **Leading to communication blackouts**

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Literature

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- ► ETSI TR 102 862 V1.1.1: “Intelligent Transport Systems (ITS); Performance Evaluation of Self-Organizing TDMA as Medium Access Control Method Applied to ITS; Access Layer Part”.
- ► Hadded M. et al. “TDMA-based MAC Protocols for Vehicular Ad Hoc Networks: A Survey, Qualitative Analysis and Open Research Issues”. Communications Surveys and Tutorials, IEEE Communications Society, Institute of Electrical and Electronics Engineers, 2015.