Behavior of channel access in 3GPP Rel-14 PC5 LTE-V2X mode 4

1 In a subframe *n* when a packet is passed to MAC buffer and the vehicle decided to perform resource reselection, a vehicle selects the time-frequency resource in a uniformly random manner among the candidate time-frequency resources in the predetermined selection window (in our case, the selection window is subframes [*n+1*, *n*+100]). The candidate time-frequency resources are determined as follows:

1.1 The vehicle monitors resources in the past 1 sec (i.e., subframes *n* -1000, *n* -999, …, *n*-1), i.e., the sensing period, except for those in which its transmissions occur.

1.2 The vehicle excludes any candidate resource at a subframe *m* in the selection window from the candidate resources if the vehicle didn't monitor the resources in the subframes *m*-100**j* (for any integer $j \in \{1, 2, \ldots, 10\}$) in the sensing period due to its transmission.

1.3 The vehicle further excludes candidate resources that were already reserved by other vehicles from the candidate resources if the corresponding PSSCH-RSRP (PSSCH Reference Signal Received Power) of the received PSCCH that reserved a candidate resource is larger than a threshold Γ. The initial value of the threshold is set relatively low (e.g., -123dBm/15kHz). If the number of candidate resources is smaller than 20% of the total resources in the selection window due to the exclusion of the reserved resources, the threshold Γ is increased by 3dB until 20% candidate resources are available to select among.

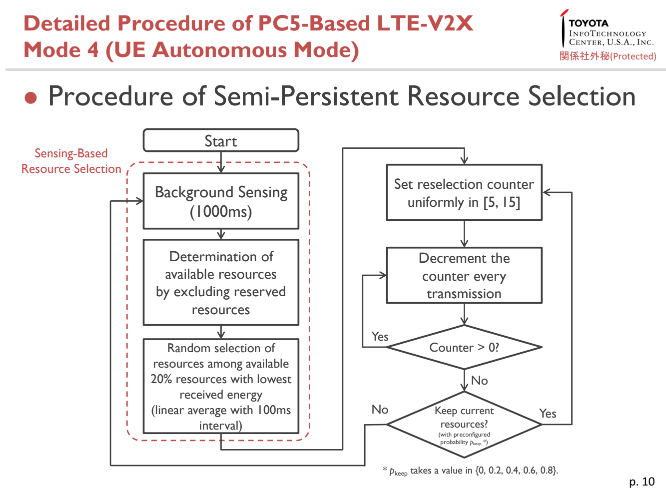
1.4 The vehicle calculates the corresponding S-RSSI (Sidelink Received Signal Strength Indicator) of each candidate resource at a subframe *x* as a linear average over the S-RSSIs of the monitored resources at subframes *x*-100**j* (for any integer $j \in \{1, 2, \ldots, 10\}$) (i.e., $\sum_{j=1}^{10} \mathrm{RSSI}_{x-100*j}/10$) in the sensing period with 100ms interval for each sub-channel (Note: this 100ms averaging interval is independent of the selection window size). (Note: here, we differentiate the S-RSSIs of no packet collision, 2 packet collision, 3 packet collision, and so on.)

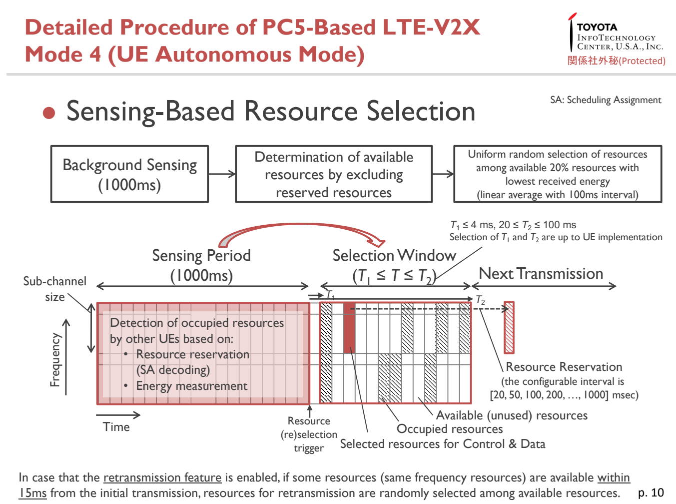
1.5 The vehicle determines 20% best resources among the total resources in the selection window (i.e., in our case, 20% resources corresponds to 40 resources for 100ms selection window) in terms of the lowest average S-RSSI calculated in the procedure 1.4. If there are multiple resources having the same S-RSSI, the vehicle ranks them randomly.

2 The vehicle sets a resource reselection counter (integer) uniformly in the range [5, 15]. This counter is decremented after every transmission.

3 When the resource reselection counter is decremented to zero, the vehicle determines whether to keep the current time-frequency resource for the subsequent transmissions in future intervals or not with the predetermined probability p_{keep} (probability to keep the current resources, where $p_{keep} \in \{0, 0.2, 0.4, 0.6, 0.8\}$). If the vehicle decides to keep the current resource, the vehicle starts over from the procedure 2 using the same time-frequency resources and a new random resource

reselection counter value (note: resource reservation continues to be used for the next transmission). If the vehicle decides to select a new resource, the vehicle starts over from the procedure 1 (note: resource reservation is not used in the last packet before resource reselection).





Example of Sub-Channel Setting

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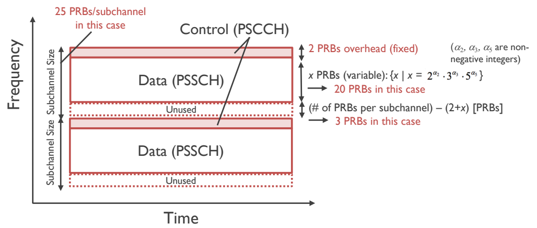

- For sub-channel size* of 25 PRBs
  - PSCCH size: 2 PRBs (fixed)
  - PSSCH size: 20 PRBs
  - In this case, 3 PRBs are unused.

*The configurable sub-channel size in case of adjacent PSCCH-PSSH is 5, 6, 10, 15, 20, 25, 50, 75, and 100.

PHY Parameters of V2X Sidelink

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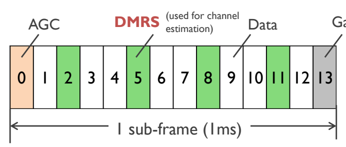
- The PHY parameters are the same as Rel-12/13 sidelink except DMRS density.



The density of DMRS is increased from 2 to 4 per sub-frame for better channel tracking in high vehicle mobility (up to 250km/h relative speed).

AGC: Automatic Gain Control
DMRS: DeModulation Reference Signal
SC-FDMA: Single-Carrier Frequency Division Multiple Access

Note: the same frame structure above is used for both control and data.

Access Scheme	SC-FDMA
Modulation	QPSK, 16QAM
Channel Coding	Turbo Coding (for data), Convolutional code (for control)
Bandwidth	10, 20 MHz
Sub-Carrier Spacing	15 kHz
Cyclic Prefix Length	Normal: 4.7 µs
	Long: 16.7 µs
# of MIMO streams	1

Parameters (default):

Carrier frequency: 5.9 GHz

Tx power: 20 dBm

Tx/Rx antenna gain: 0 dBi

Noise figure: 9 dB

Tx/Rx antenna height: 1.5 m

System bandwidth: 10 MHz = 50 PRBs

Sub-channel size: 5 MHz = 25 PRBs (i.e., up to 2 vehicles can transmit packets simultaneously in 10MHz system bandwidth) (Note: in 3GPP specs, the configurable sub-channel size in case of adjacent PSCCH-PSSCH is 5, 6, 10, 15, 20, 25, 50, 75, and 100.)

PSCCH and PSSCH size: Among 25 PRBs in each sub-channel, 2 PRBs (fixed) for PSCCH and 20 PRBs for PSSCH (thus the remaining 3 PRBs are unused) (Note: in 3GPP specs, the number of PRBs for PSSCH is the largest integer that fulfils $2^{\alpha_2} \cdot 3^{\alpha_3} \cdot 5^{\alpha_5}$, where α_2, α_3, α_5 are non-negative integers.)

Probability to keep the current resource p_{keep}: 0, 0.2, 0.4, 0.6, 0.8

Sensing window: T_1 = 1 ms, T_2 = 100 ms

Channel model:

- Path loss: ITU-R P1411 LOS path loss with 5.9 GHz and 1.5m antenna height for both Tx and Rx, where the path loss is updated every update of vehicles' locations
- Shadowing: Log-normal shadowing, where the shadowing coefficient is updated every packet transmission as follows:
  - $As + \sigma u\sqrt{1 - A^2}$ [dB], where $A = \exp\left(\frac{-t_{diff}}{CohereTime}\right)$ with *CohereTime* = 1.5 sec (parameter) and t_{diff} [sec] is the time that has lapsed since last computation of shadowing coefficient for this Tx-Rx link
    - *s* is the shadowing coefficient computed last time for this Tx-Rx link
    - *u* is drawn from a i.i.d normal distribution with the mean = 0 dB and standard deviation 0.001 dB (parameter)
    - σ is 5.0688 if the Tx-Rx distance <= 250m. Otherwise 4.73887
    - The initial value of the shadowing coefficient is given by σu [dB].
  - The shadowing coefficient from the vehicle A to the vehicle B and one from the vehicle B to the vehicle A are the same for a given time *t*. The shadowing coefficient between the vehicle A and the vehicle B is updated every packet transmission from the vehicle A to the vehicle B and vice versa according to the autocorrelation model above.

- Fast fading: the fading amplitude follows Nakagami-*m* distribution with a random phase following the uniform distribution in the range [0, 2π], where the fading coefficient is updated every subframe following i.i.d. model

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  - The average fading power Ω is 1 (fixed) and the parameter *m* is distance-dependent given by for V2V distance *d* [m]:

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$$m(d) = \begin{cases} 3, & d < 50 \\ 1.5, & 50 \le d < 150 \\ 1, & d \ge 150 \end{cases}$$

- For 2 Rx antenna scenario, 2 Rx antennas experience uncorrelated fast fading (i.e., the fast fading coefficients for 2 Rx antennas are independently generated and updated), while they experience the same path loss and shadowing.

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Performance metrics:

- Packet Reception Ratio (PRR): For one Tx packet, the PRR is calculated by *X* / *Y*, where *Y* is the number of vehicles that located in the range (*a*, *b*) from the Tx, and *X* is the number of vehicles with successful reception among *Y*. The average PRR is calculated as $(X_1+X_2+X_3+....+X_n)/(Y_1+Y_2+Y_3+....+Y_n)$ where *n* denotes the number of generated messages in simulation.
  - Figure 1: V2V distance vs. average PRR (for V2V distance bins of *a*=*i**20 meters, *b*=(*i*+1)*20 meters for *i*=[0, 25])
  - Figure 2: CDF of PRR for different V2V distance bins (samples within range [*i**20, (*i*+1)*20]m with for *i* = [0, 15])
- Packet Inter-Reception (PIR): Time elapsed between two successive successful reception of two different packets transmitted from vehicle A to vehicle B
  - Figure: CDF of PIR for different V2V distance bins (samples within range [*i**20, (*i*+1)*20]m with for *i* = [0, 15])
- Information Age (IA): Time between the current measuring timestamp ($i * t_{period}$) and the packet generation timestamp (t_i) at a transmitter vehicle A for last successfully received packet transmitted from vehicle A to vehicle B, where *i* = 0, 1,..., and t_{period} = 100ms
  - Figure: CDF of IA for different V2V distance bins (samples within range [*i**20, (*i*+1)*20]m with for *i* = [0, 15])
- End-to-end latency: Time difference between the packet generation timestamp at a transmitter vehicle A and packet arrival at a receiver vehicle B (for successfully received packets)
  - Figure: CDF of end-to-end latency (samples within V2V distance range [0, 320]m)

Constraint:

- Each vehicle uses 1 Tx antenna and 2 Rx antennas (Note: in 3GPP specs, at least 2 Rx antennas are required to ensure the communication performance). The maximum ratio combining (MRC) is performed for reception. We assume that fast fading coefficients for 2 Rx antennas are uncorrelated, while the path loss and shadowing coefficients are the same for 2 Rx antennas.

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  - The received power of the target signal after MRC without the noise effect, $P_r^{(MRC)}$ [W], is given by:
  $$P_{\mathrm{r}}^{(\mathrm{MRC})} = L_{PL} \cdot L_S \cdot (|h_1|^2 + |h_2|^2) \cdot P_t$$
  where L_{PL} is path loss (linear domain), L_S is shadowing loss (linear domain), h_k (k=1,2) is the fast fading complex coefficient of Rx antenna k, and P_t [W] is the transmit power.

  - The sum of interference signals after MRC without the noise effect, I [W], is given by:
  $$I = \sum_i L_{PL,i} \cdot L_{S,i} \cdot (|h_1^* h_{1,i} + h_2^* h_{2,i}|^2) \cdot P_t$$
  where $L_{PL,i}$ is the path loss (linear domain) of i-th interferer, $L_{S,i}$ is shadowing loss (linear domain) of i-th interferer, $h_{k,i}$ (k=1,2) is the fast fading complex coefficient between Rx antenna k and i-th interferer, and * is the conjugate of a complex value.

  - The SINR γ (linear domain) after MRC is given by:
  $$\gamma = \frac{P_{\mathrm{r}}^{(\mathrm{MRC})}}{N + I}$$
  where N is the noise power and I is the sum of interference signals. When we look up a plot of link level simulation, we use the average SINR per Rx antenna $\gamma' = \gamma/2$.

- To determine the success or failure of packet reception, we look up the table of SNR vs. packet error rate (link level simulation result) according to the computed SINR above. First, we generate a random number in the range [0,1]. If the random number is greater than the packet error rate looked up from the link level simulation result, the packet is considered as successfully received; otherwise considered as failure.

- The Tx power of PSCCH signal is 3 dB higher than one of PSSCH signal. This means that for the total Tx power P [W], the Tx powers of PSCCH and PSSCH signals are given by P_{PSCCH} = P*2/3 [W] and P_{PSSCH} = P*1/3 [W], respectively.

- Every vehicle generates a packet every 100ms (deterministic). The generation timing of the first packet for each vehicle follows uniform random distribution between 0 – 100ms, which is independent across vehicles.

- All vehicles are synchronized in time and frequency. Time-frequency resources are divided by the granularity of the resource size of a subframe (1ms) * sub-channel size [Hz]. Every vehicle uses one resource (i.e., 1ms x sub-channel size [Hz]) for each packet transmission.
- Every vehicle notifies the reservation of the time-frequency resource for the next transmission in PSCCH by indicating the time interval between the current transmission and the next transmission (in our case, this time interval is always 100ms) in all the packets except the last packet before resource reselection. The last packet before resource reselection does not reserve the resource for the next transmission. The resource reservation interval is configurable among the values {20, 50, 100, 200, 300, 400, …, 1000} ms. Other vehicles take into account that resource reservation information only if the packet including resource reservation information in PSCCH is successfully received.
- No packet retransmission is assumed (though 3GPP spec allows it).
- Channel busy ratio (CBR) is measured at each packet transmission over the past 100ms duration. If a resource is occupied by at least one packet, the resource is considered as busy. Then, the average CBR (averaged across vehicles and time domain) for each vehicle density is calculated.
- In S-RSSI calculation, we calculate the S-RSSI of each Rx antenna port and use the higher S-RSSI output among 2 S-RSSI outputs of 2 Rx antennas.

Definitions (cf. 3GPP TS 36.214):

5.1.28 Sidelink Received Signal Strength Indicator (S-RSSI)

Definition	Sidelink RSSI (S-RSSI) is defined as the linear average of the total received power (in [W]) per SC-FDMA symbol observed by the UE only in the configured sub-channel in SC-FDMA symbols 1, 2, …, 6 of the first slot and SC-FDMA symbols 0,1,…, 5 of the second slot of a subframe The reference point for the S-RSSI shall be the antenna connector of the UE. If receiver diversity is in use by the UE, the reported value shall not be lower than the corresponding S-RSSI of any of the individual diversity branches
Applicable for	RRC_IDLE intra-frequency, RRC_IDLE inter-frequency, RRC_CONNECTED intra-frequency, RRC_CONNECTED inter-frequency

5.1.29 PSSCH Reference Signal Received Power (PSSCH-RSRP)

Definition	PSSCH Reference Signal Received Power (PSSCH-RSRP) is defined as the linear average over the power contributions (in [W]) of the resource elements that carry demodulation reference signals associated with PSSCH, within the PRBs indicated by the associated PSCCH. The reference point for the PSSCH-RSRP shall be the antenna connector of the UE. If receiver diversity is in use by the UE, the reported value shall not be lower than the corresponding PSSCH-RSRP of any of the individual diversity branches
Applicable for	RRC_IDLE intra-frequency, RRC_IDLE inter-frequency, RRC_CONNECTED intra-frequency, RRC_CONNECTED inter-frequency

NOTE: The power per resource element is determined from the energy received during the useful part of the symbol, excluding the CP.

5.1.30 Channel busy ratio (CBR)

Definition	Channel busy ratio (CBR) measured in subframe *n* is defined as follows: - For PSSCH, the portion of sub-channels in the resource pool whose S-RSSI measured by the UE exceed a (pre-)configured threshold sensed over subframes [*n-100, n-1*]; - For PSCCH, in a pool (pre)configured such that PSCCH may be transmitted with its corresponding PSSCH in non-adjacent resource blocks, the portion of the resources of the PSCCH pool whose S-RSSI measured by the UE exceed a (pre-)configured threshold sensed over subframes [*n-100, n-1*], assuming that the PSCCH pool is composed of resources with a size of two consecutive PRB pairs in the frequency domain.
Applicable for	RRC_IDLE intra-frequency, RRC_IDLE inter-frequency, RRC_CONNECTED intra-frequency, RRC_CONNECTED inter-frequency

NOTE: The subframe index is based on physical subframe index

5.1.31 Channel occupancy ratio (CR)

Definition	Channel occupancy ratio (CR) evaluated at subframe *n* is defined as the total number of sub-channels used for its transmissions in subframes [*n-a*, *n-1*] and granted in subframes [*n*, *n+b*] divided by the total number of configured sub-channels in the transmission pool over [*n-a*, *n+b*].
Applicable for	RRC_IDLE intra-frequency, RRC_IDLE inter-frequency, RRC_CONNECTED intra-frequency, RRC_CONNECTED inter-frequency

NOTE 1: *a* is a positive integer and *b* is 0 or a positive integer; *a* and *b* are determined by UE implementation with *a+b+1 = 1000*, a >= 500, and n+b should not exceed the last transmission opportunity of the grant for the current transmission.

NOTE 2: CR is evaluated for each (re)transmission.

NOTE 3: In evaluating CR, the UE shall assume the transmission parameter used at subframe *n* is reused according to the existing grant(s) in subframes [*n+1*, *n+b*] without packet dropping.

NOTE 4: The subframe index is based on physical subframe index.

NOTE 5: CR can be computed per priority level