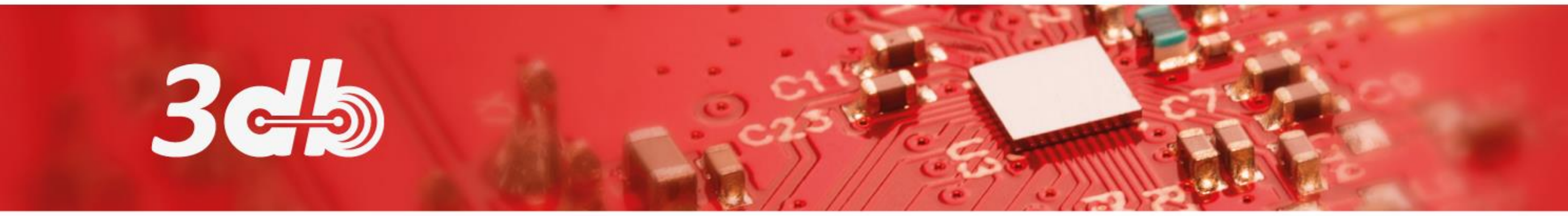

THEORETICAL CALCULATIONS OF HRP AND LRP LINK MARGIN

SYNC and SFD are parts of the IEEE 802.15.4z ranging packet that are good indicators of the link margin performance of UWB ranging transceivers. To successfully receive and timestamp a ranging packet, an UWB receiver must be able to reliably detect at least these two parts of the packet.

Since the SYNC is typically used for clock offset extraction, synchronization, and channel impulse response estimation, it is difficult to use it for a performance comparison in terms of link margin. On the other hand, the SFD, although used for coarse ranging and RSSI, shall be detected. Therefore, the SFD determines link margin performance because its detection can be quantified by known communication mechanisms (pattern detection).

SYNC	SFD	STS

a) HRP ranging packet with STS, no payload

SYNC	SFD	CHALLENGE (PAYLOAD)

b) LRP secure distance bounding packet

To simplify the following theoretical calculations, we assume that:

- The propagation is in free space, i.e., only one line-of-sight (LOS) path between Tx and Rx, no multiple paths that could cause inter-pulse interference (IPI);
- HRP and LRP are compared on their mandatory configurations recommended for car access control; see Figure: a) HRP: SYNC+SFD+STS, b) LRP: SYNC+SFD+CHALLENGE;
- A maximum mean power spectral density (PSD) of -41.3 dBm/MHz (or 75 nW/MHz averaged over 1 ms) is considered in the calculation of the total transmitted energy;
- Tx PSD is not suffering from spectral lines due to periodicity in the RF signal (assumed perfectly dithered) and the spectrum optimally occupy the channel bandwidth;
- Tx and Rx are perfectly aligned in timing (no degradation due to clock offset);
- Rx performance is assuming an optimal reception method (matched filter implementation).
- For the calculations below to be valid, the other parts of the message (SYNC, STS or CHALLENGE) must have a performance at least equal to that of the SFD.

Transmitter (TX) side: main parameters

Parameters	Symbol	Unit	HRP coherent	LRP non-coherent	LRP coherent	Comments
Channel bandwidth	BW_{-3dB}	MHz	500	2·250	2·250	-3dB bandwidth (split in two sub-bands for LRP)
Number of pulses in SYNC	$N_{p,SYNC}$	-	4096	176	176	HRP: according to CCC mandatory mode
Number of pulses in SFD	$N_{p,SFD}$	-	256	128	128	LRP: according to car access mode deployed on market
Number of pulses in CHALLENGE	$N_{p,SEC}$	-	4096	256	256	HRP: STS (undefined security level) / LRP: for 32-bit security
Total number of pulses in packet	$N_{p,TOT}$	-	8448	560	560	
Ranging packet duration	T_{pckt}	µs	135.4	140	140	LRP PRF = 4 MHz / HRP PRF = 62.4 MHz
Energy per transmitted pulses	$\mathbf{E_{p,TX}}$	**pJ**	**4.4**	**67**	**67**	PSD = 75 nW/MHz, BW = 500 MHz, T = 1 ms → $E_{p,TX}$ = 37.5 nJ / $N_{p,TOT}$

Due to the reduced number of pulses emitted, the energy per pulse and thus the signal-to-noise ratio at the transmitter is significantly higher for the LRP Standard.

Receiver (RX) side: SFD parameters

Parameters	Symbol	Unit	HRP coherent	LRP non-coherent	LRP coherent	Comments
Number of symbols in SFD	N_{symb}	-	8	8	8	Same number of symbols is compared
Number of pulses per SFD symb.	N_{pps}	-	32	16	16	Average number of active pulses per SFD symbol
Nominal processing gain	PG	dB	3.01	2.25	3.01	Coh. Rx: 3.01 dB / Non-coh. is 2.25 dB achieved in 3db IC
Processing gain per SFD symbol	PG_{symb}	dB	15.05	9.0	12.04	$PG_{symb} = PG \cdot \log_2(N_{pps})$, PG is pulse energy accumulation in symbol
Mean energy per RX SFD symbol	$E_{symb,Rx}$	pJ	142	532	1071	Mean energy of the received SFD symbol (at 0 dB path loss) $E_{symb,RX} = E_{p,TX} \cdot 10^{PGsymb/10}$
Pulse signal-to-noise ratio at RX	$\mathbf{SNR_{RX}}$	**dB**	**105.4**	**111.1**	**114.1**	$\mathbf{SNR_{RX} = E_{symb,RX}/N_0}$, $\mathbf{N_0 = 4.41 \cdot 10^{-21}}$ **[W/Hz] is noise PSD**
Required SNR at RX for 10^{-3} BER	SNR_{BER}	dB	10 (BPSK, ternary)	11 (non-coh. BFSK)	10 (coh. BFSK)	10^{-3} BER is at least required for a 1% PER on 8 SFD symbols
Overall receiver noise figure	NF	dB	5	5	5	Typical receiver front-end specification
Link margin	**LM**	**dB**	**90.4**	**95.1**	**99.1**	$\mathbf{LM = SNR_{RX} - SNR_{BER} - NF}$

Despite its very high complexity (large silicon area), current consumption and latency due to heavy digital post-processing, the considered HRP implementation doesn't perform better in terms of link margin than an ultra-low power, non-coherent, secure, zero-latency and silicon-proven LRP implementation. The link margin, calculated from the SFD performance, theoretically gives a 4.7 dB advantage to a non-coherent LRP implementation and 9 dB to a coherent LRP implementation compared to HRP.

A further discussion below is enumerating qualitatively additional practical impairments of each ranging technologies and their net effect on the link margin:

	HRP coherent	**LRP non-coherent**	**LRP coherent**
Phase alignment	In practice, the 7 dB requirement in SNR_{RX} value is hardly achievable because of the non-perfect clock alignment. For BPSK, an error of ±λ/16 (±22.5°) in carrier phase alignment is degrading the sensitivity by approximately 1 dB. → $\Delta PG_{SFD,HRP} \approx 1$ dB	In non-coherent LRP no phase alignment is required, the efficiency of the processing gain of a non-coherent detection scheme is already accounted for in the nominal PG value of 2.25 dB (achieved by the 3db IC).	Same remark as for HRP applies here for a coherent LRP implementation. → $\Delta PG_{SFD,c\text{-}LRP} \approx 1$ dB;
Tx PSD	The PSD of an HRP signal is highly fluctuating due to the random nature of the pulse polarity and the high PRF. This high PRF generates a high IPI in the 1 MHz "bin" of a spectrum analyzer and a certain margin must be added to the transmitted PSD. → $\Delta PSD_{HRP} \approx 2$ dB	Non-coherent LRP has perfect dithering in terms of TX PSD owing to the random phase; moreover, the low pulse repetition rate prevents further PSD reduction. However, the pulse shape used in the current implementation (Gaussian shape) does not optimally fit the rectangular spectral mask → $\Delta PSD_{nc\text{-}LRP} \approx 2$ dB	The PSD of LRP signal may suffer from spectral lines due periodicity in the transmitted signal (especially during the SYNC portion of the packet). Next implementations of the LRP transmitter will use better pulse shapes (RRC shape) to optimally fit spectral mask → $\Delta PSD_{c\text{-}LRP} \approx 1.5$ dB
Link Margin	**LM_{actual} < 90.4 – 1 – 2 = 87.4 dB** **In line with known implementations of HRP**	**LM_{actual} = 95.1 – 2 = 93.1 dB** **In line with 3db IC implementation**	**LM_{actual} = 99.1 – 1 – 1.5 = 96.6** **In evaluation for next generation LRP**