LunaNet AFS Properties and Signal Band

Presented by: Floor Melman, ESA / Juan Crenshaw, NASA GSFC / Masaya Murata, JAXA

Contributors:

Cheryl Gramling, NASA HQ

Philip Dafesh, NASA / Aerospace

Brian C. Peters, NASA GSFC

Richard Swinden, ESA

Cosimo Stallo, ESA

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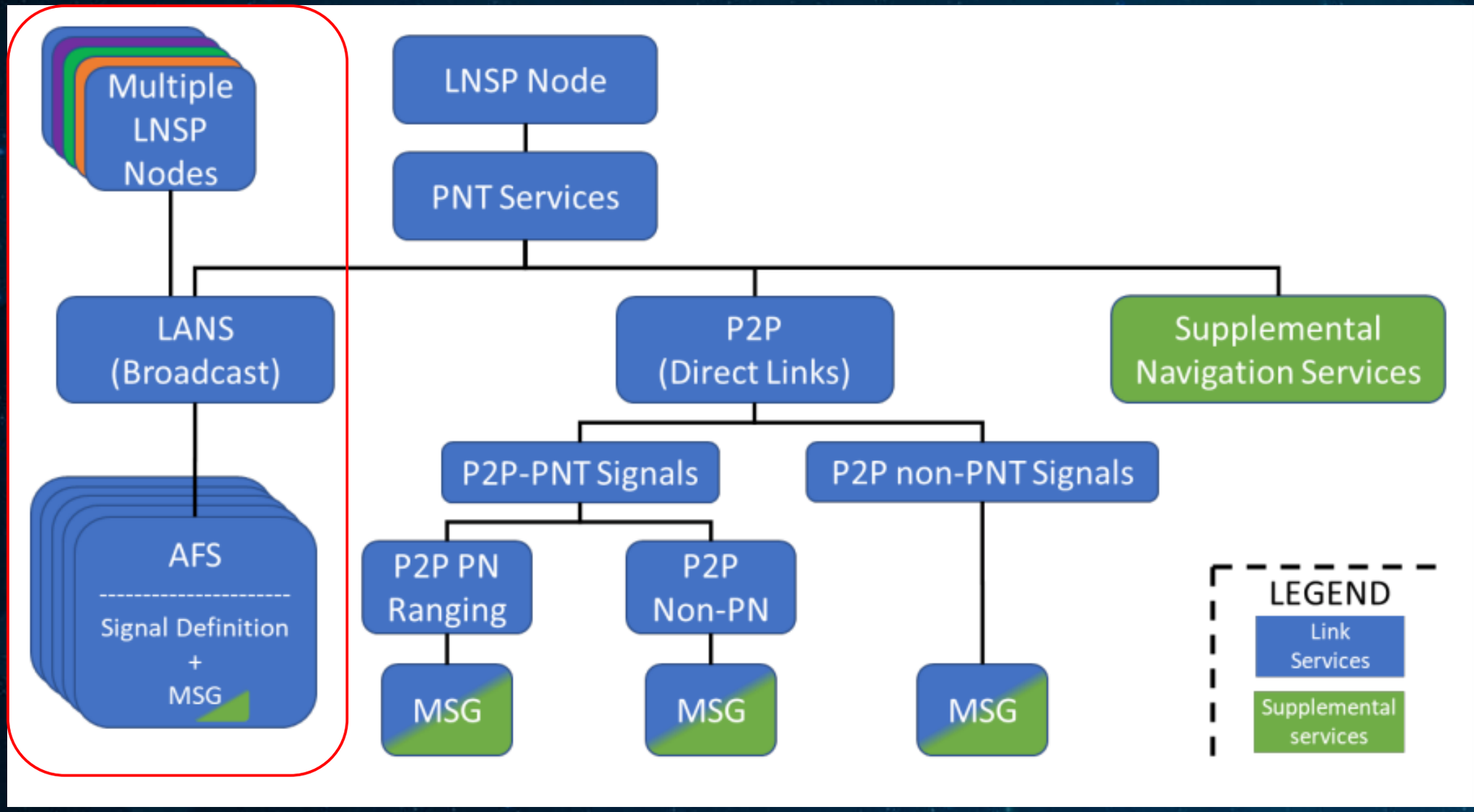
Vienna, Austria

Topics

- AFS Frequency Modulation
- AFS Spreading Codes
- AFS Navigation Message

Augmented Forward Signal



Frequency Selection

- AFS Band: 2483.5 – 2500 MHz
- AFS Carrier: 2492.028 MHz (closest multiple of f_0 = 1.023 MHz)
- Reference Bandwidth: 15.944 MHz

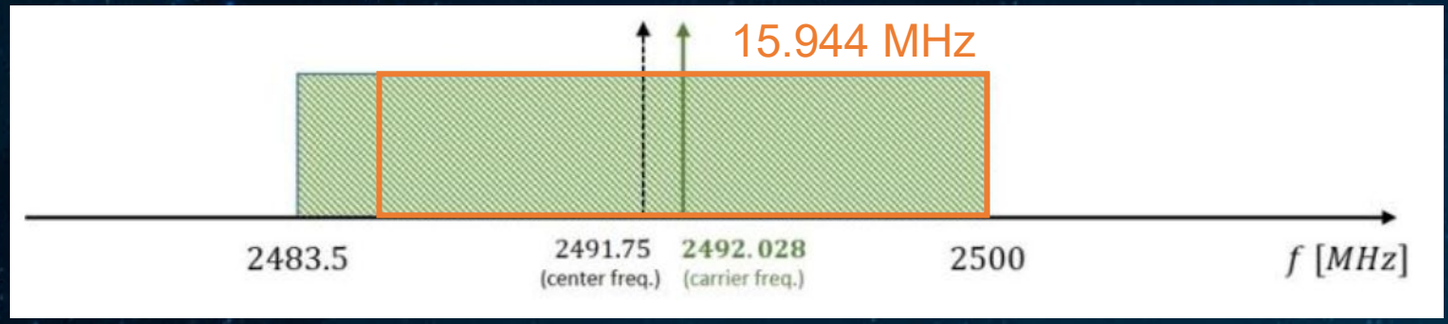


Table 2: Recommended Frequency Bands for RNSS or RDSS Applications in the Lunar Vicinity

Link	Frequency
Earth-based GNSS to Lunar Orbit and Lunar Surface	1164-1215 MHz 1215-1300 MHz 1559-1610 MHz
In-situ Lunar based RNSS/RDSS to Lunar Orbit and Lunar Surface	2483.5-2500 MHz

Space Frequency Coordination Group

Recommendation SFCG 32-2R5

COMMUNICATION AND POSITIONING, NAVIGATION, AND TIMING FREQUENCY ALLOCATIONS AND SHARING IN THE LUNAR REGION

THE SFCG

CONSIDERING

a) that a regional communication network at the Moon, also including Positioning, Navigation, and Timing (PNT) services, can be expected in the foreseeable future as missions to the lunar region increase in number and variety;

b) that frequencies for direct communication between a spacecraft in the lunar region and an earth station are provided in the existing allocations to Space Research Service (SRS);

c) that separate frequencies are needed in the lunar region for compatible local communications between a surface vehicle and an orbiter, between surface vehicles, and between orbiters;

d) that major criteria for allocating frequencies in the lunar region include RF compatibility, technology availability and performance, mission scenarios, cost, and ability to conduct testing and emergency support from the Earth;

e) that the major benefit of an agreed frequency plan for the lunar region enables interoperability and sharing of communications and PNT infrastructure and service assets to support individual or joint exploration missions to accomplish complex objectives;

f) that envisioned lunar missions will involve complex communications architectures using earth stations that can communicate with near-Earth relay satellites, lunar orbiting satellites, and lunar surface elements in view of Earth;

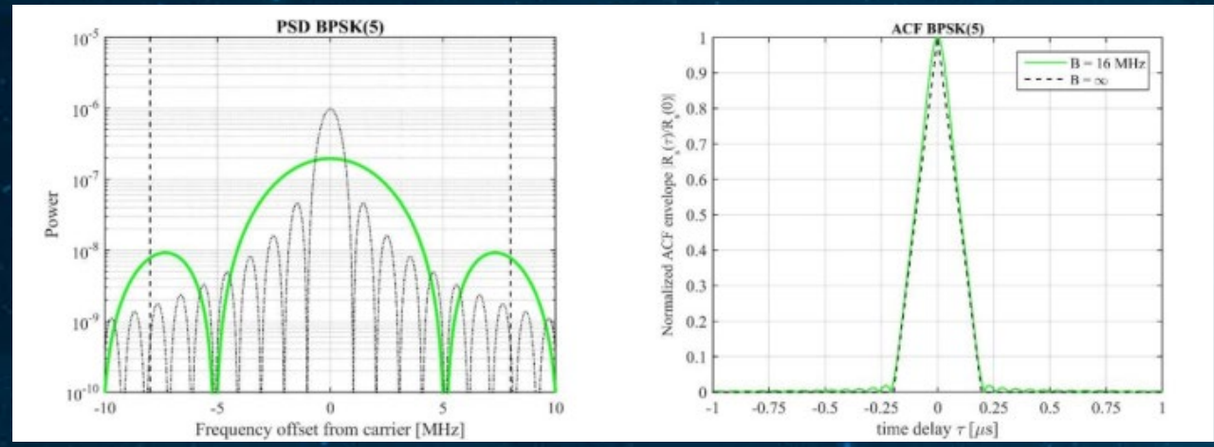
g) that it is envisioned that missions in the lunar region will employ Lunar Relay Satellites (LRS) to allow relay communication coverage and to forward data gathered from lunar surface elements to earth stations;

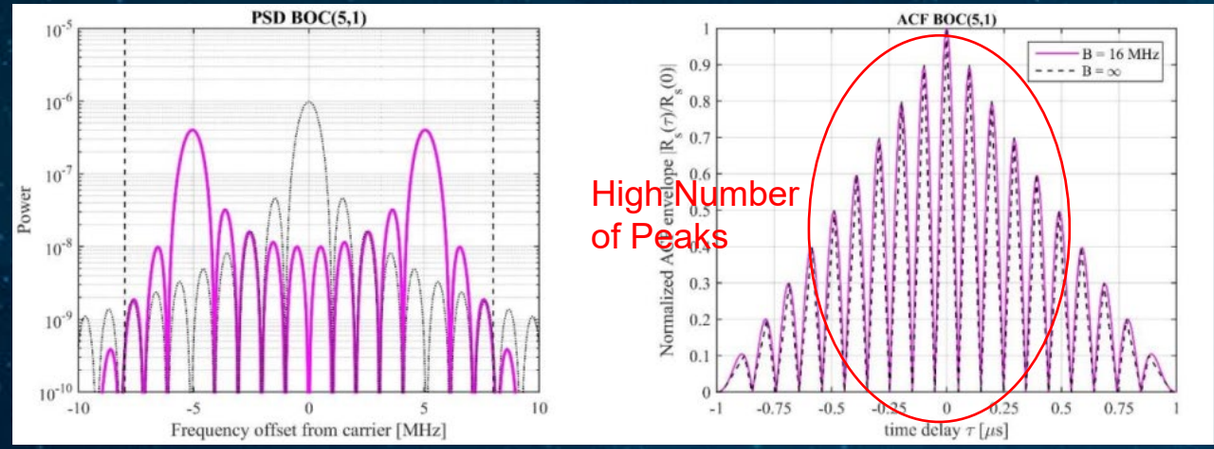
h) that it is envisioned that missions in the lunar region by multiple administrations either independently or jointly can occur during the same time period and each mission may employ

Modulation Candidates

1. Data Channel
   - Ensuring signal energy to be concentrated around carrier
   - Limit OBUE for given receiver bandwidth
   - **<u>Selected candidate: BPSK(1)</u>**

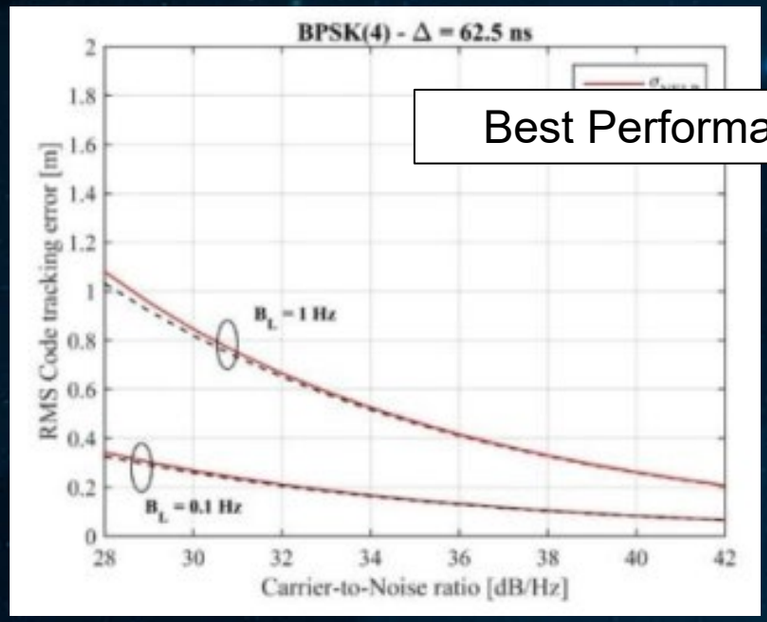
2. Pilot Channel
   - Optimizing optimized tracking performance
   - Candiates: BPSK vs BOC
     - BPSK(4)
     - BPSK(5)
     - BOC(2,2)
     - BOC(5,1) -> Large number of peaks (18)
     - BOC(5,2) -> Large number of peaks (8)



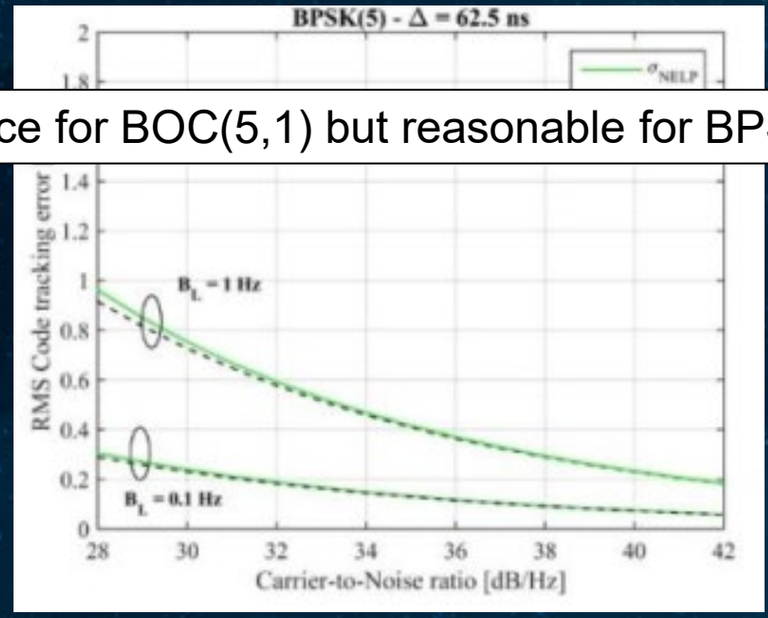


Acquisition and Tracking Performance

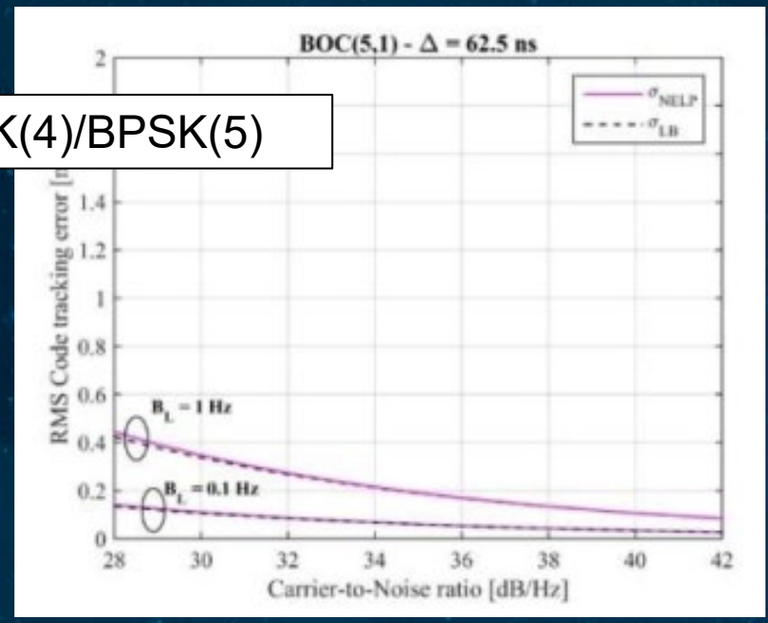
BPSK(4)



BPSK(5)



BOC(5,1)



Best Performance for BOC(5,1) but reasonable for BPSK(4)/BPSK(5)

Data/Pilot Power Share

C/N_0 (data+pilot)	75/25		50/50		25/75	
	K	dwell time	K	dwell time	K	dwell time
27 dB/Hz	1583	1583 ms	433	433 ms	208	208 ms

25% power on Data would compromise data rate objective

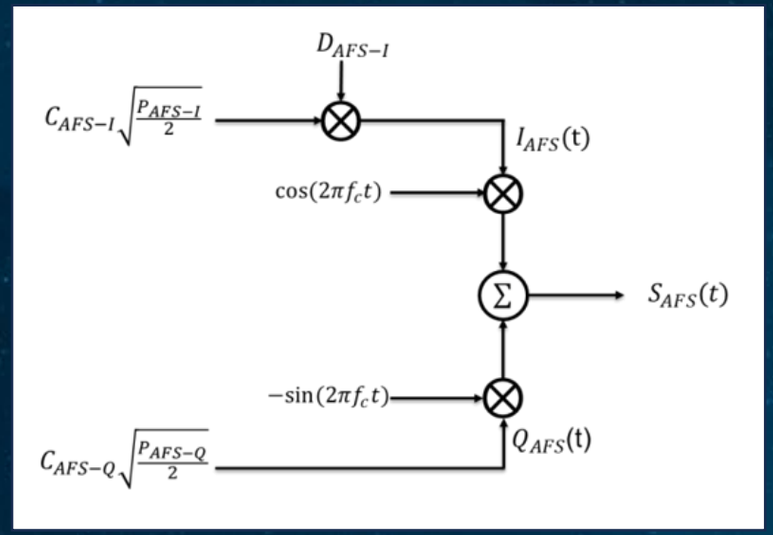
Modulation Trade-Off

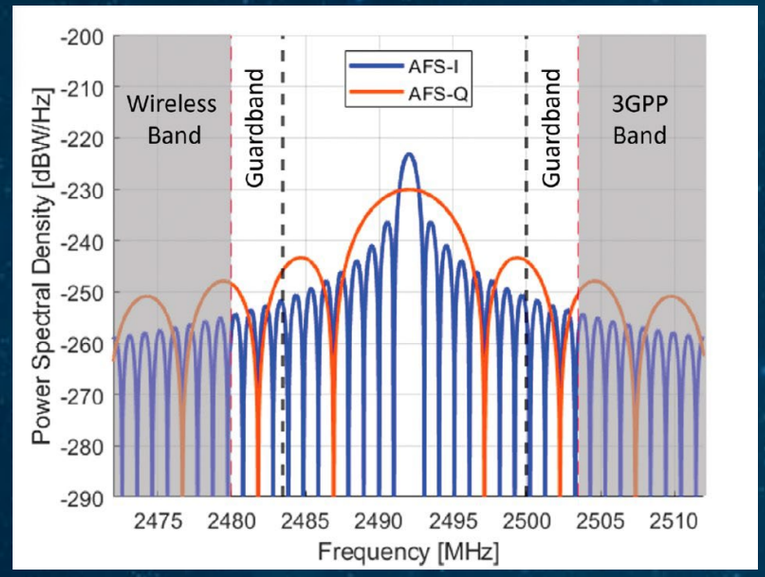
	BPSK(4)	BPSK(5)	BOC(5,1)
Auto Correlation Function	No side peaks	No side peaks	Large number of side peaks (18) inrease probability of false tracking
Acquisition Search Space (vs BPSK(5)	80%	100%	62.5%
Tracking Performance (CRLB) @C/N0 = 30 dB-Hz	0.82 meter	0.73 meter	0.34 meter
Intersystem interference SSC [BPSK(1)]	-69.47 dB/Hz	-70.36 dB/Hz	-84.85 dB/Hz
Multipath impact	Until 300 ns (~90 meter)	Until 250 ns (~75 meter)	Until 850 ns (~255 meter)
WiFi Interference (Ch 12) C_{WiFi}/C_{AFS} (-3 dB-Hz)	87.3	86.4	76.2
In-band interference (Rectangular BW)	3.89 MHz	4.79 MHz	2.04 MHz

AFS Modulation

AFS Signal Design

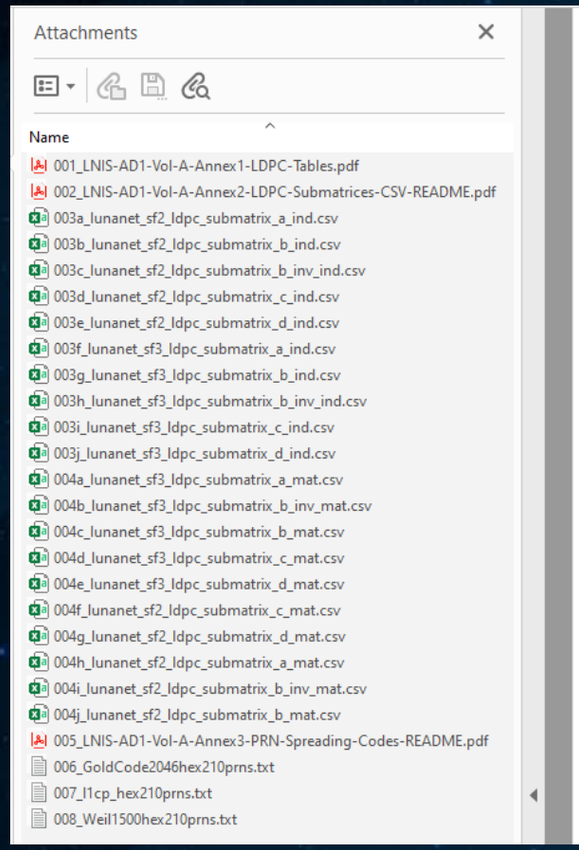
- Data-channel with 500 symb/second
- Pilot-channel with BPSK(5) for accurate robust ranging
- Power share 50/50 to enable high data-rate and robust ranging

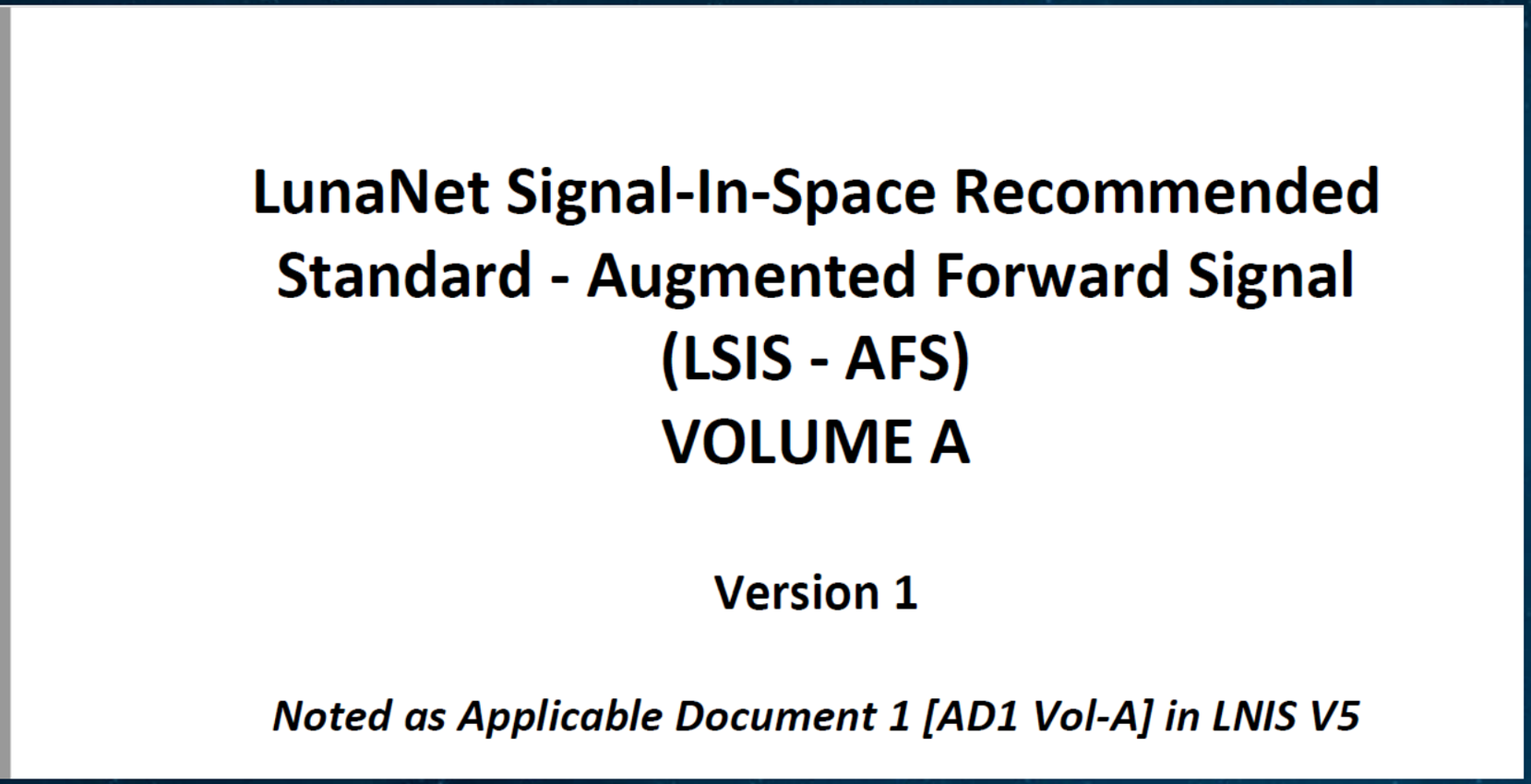




	Power Share	Modulation	Data Rate
AFS-I (Data)	50%	BPSK(1)	500
AFS-Q (Pilot)	50%	BPSK(5)	n/a

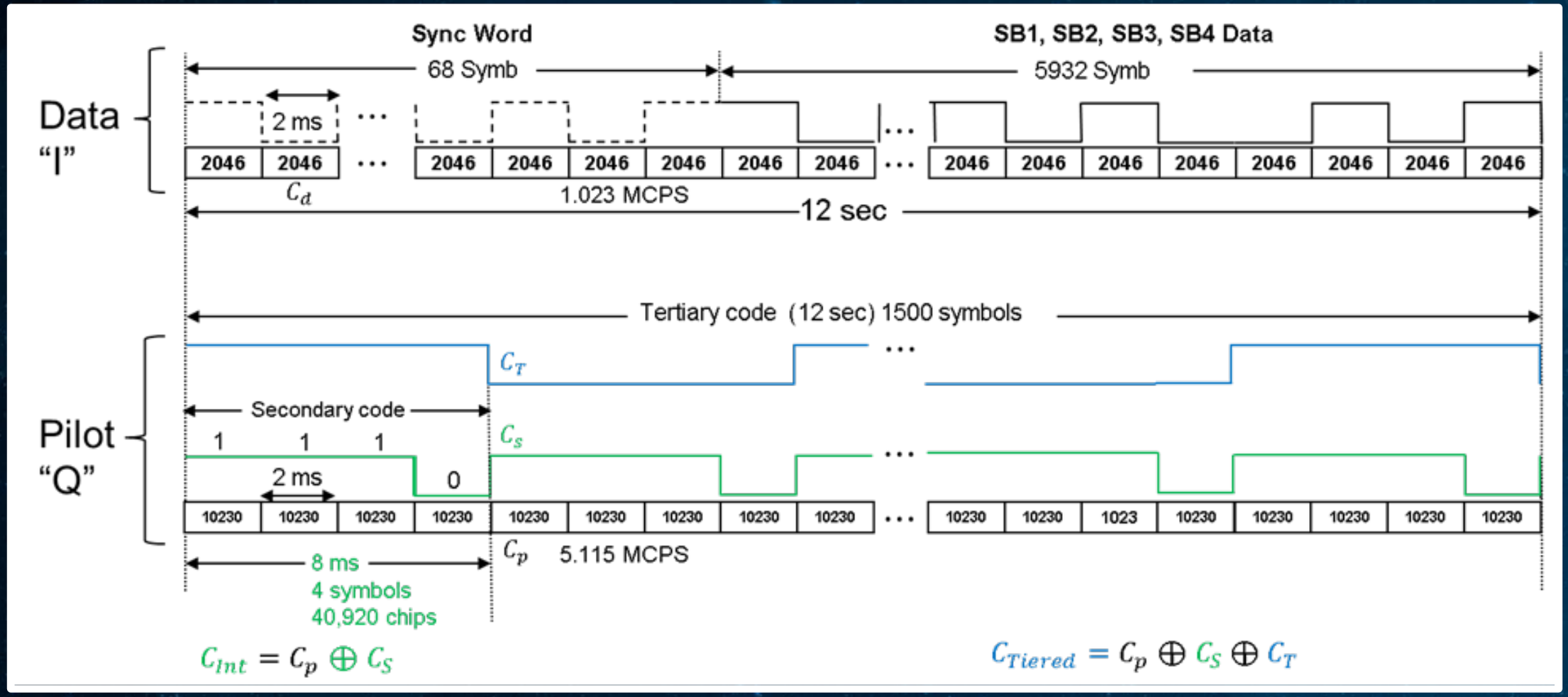
LNIS AD1 Vol-A Attachment Files





- LNIS AD1 Vol-A includes attachment files with detailed artifacts in different formats for interpreting
  - Data coding,
  - PN Sequences.

Signal Overview



Data Channel Ranging Code (I)

- The I channel employs a 1.023 Mchip/sec BPSK spreading code,
  - Its period matched to the 2 ms symbol period.
    - ➢Unlike C/A code, this permits immediate bit Sync.
- 210 Length 2046 Spreading codes were selected from a 2047 length Gold Code family short cycled by 1 chip.
  - A 2046-chip short cycled 2053-length Weil sequence was also constructed but found to have comparable correlation performance.
  - Ultimately, the Gold code was selected to simplify implementation.
- The 2046-chip AFS I channel spreading code was found to provide a 3 dB improvement 99.9 % of the time during acquisition, compared to the GPS L1 C/A spreading code and over 1 dB while tracking.

Code	C/A	C/A	C/A	C/A	Beidou	AFS-I	AFS-I
PRNs	209	50	209	50	37	210	50
Ti (ms)	1	1	2	2	2	2	2
	Acq.	Acq.	Track	Track	Acq./Track	Acq./Track	Acq./Track
Code Length (chips)	1023	1023	1023	1023	2046	2046	2046
Max (dB)	-16.5	-16.5	-19.5	-19.5	-19.8	-19.6	-20.6
RMS (dB)	-30.1	-30.1	-31.4	-31.3	-33.1	-33.1	-33.1
99% percentile (dB)	-22.7	-22.7	-23.9	-23.9	-25.5	-25.5	-25.5
99.9% percentile (dB)	-20.3	-20.3	-22.6	-22.6	-23.7	-23.7	-23.7

The 210 AFS Gold codes have performance that is comparable to BeiDou's 37 Length 2046 gold codes.

Dataless Pilot Channel (Q)

- The Q channel employs a 10230-chip, 5.115 Mchip/sec BPSK primary ranging code, C_p.
  - Like the I channel code, the 2 ms duration of the code aligns with the data symbols, therefore bit Sync is immediate.

- The primary code is modulated by a 4-chip secondary Barker sequence, C_s, assigned to each transmitter.
  - This forms an intermediate code $C_{Int} = C_p + C_s$ that provide flexibility in signal acquisition and an improved cross-correlation.
  - The 4-chip code enables users to improve antijam by 6 dB relative to the AFS primary code and L5
    - ➢ Its complexity is twice that of acquiring L5's primary code
    - ➢ Longer codes would be too complex for practical use during acquisition (e.g., L5's Neuman Hoffman codes)

	Binary Representation				NRZ Representation			
	B_4	B_3	B_2	B_0	N_4	N_3	N_2	N_1
C_0	1	1	1	0	-1	-1	-1	1
C_1	0	1	1	1	1	-1	-1	-1
C_2	1	0	1	1	-1	1	-1	-1
C_3	1	1	0	1	-1	-1	1	-1

- A tertiary code further extends the 8 ms intermediate code so the tiered code matches the 12 second data frame
  - This enables tertiary code to be used for robust frame Sync and determining absolute time to arbitrarily low C/N0,
    - ➢ Only limited by the minimum C/N_0 required for code and carrier tracking.

Comparing AFS Acquisition Alternatives

- The AFS signal provides flexible acquisition alternatives that allow trade of complexity and performance.
  - Acquisition complexity $\propto L \times R_c \times$ Number of sidebands (for all data or all pilot)*.

- The comparison below assumes that the processing gain, PG, of a signal is proportional to $R_c \times T_i$
  - Ti is limited to the repeating code duration.

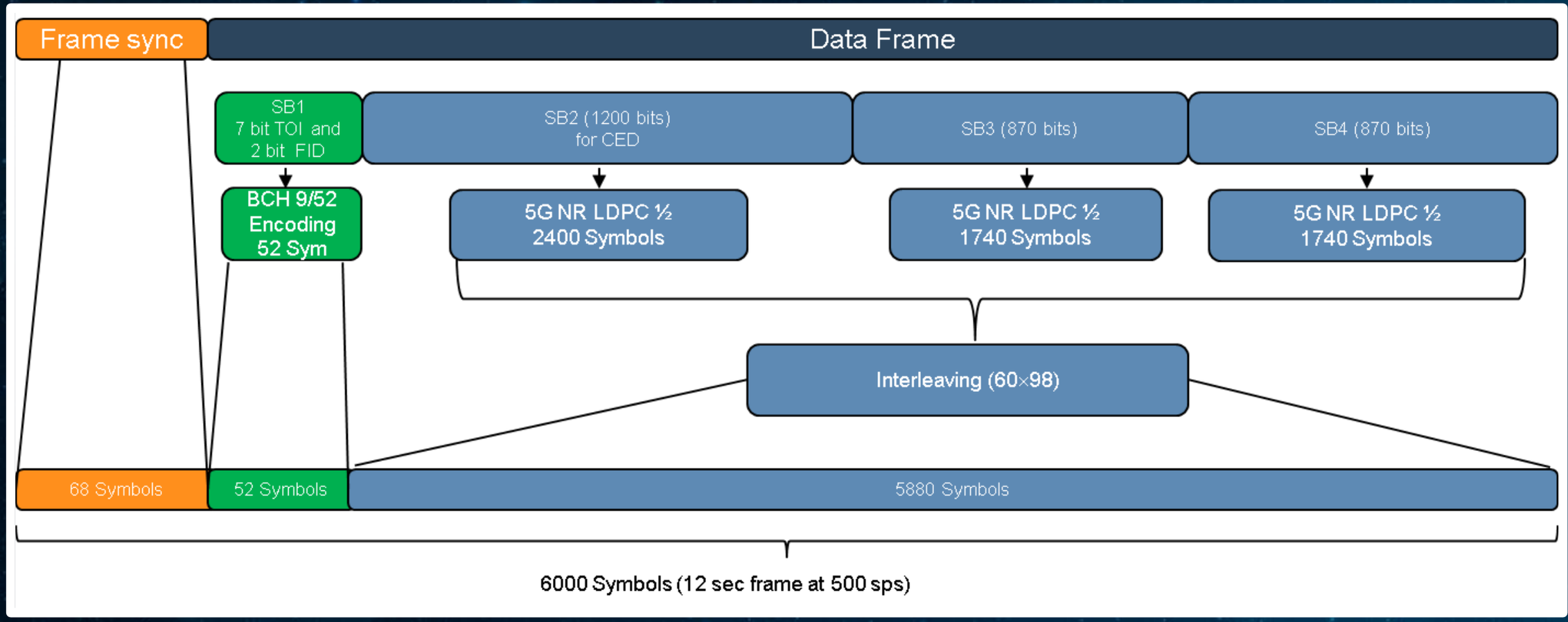
Acquisition Code	Complexity Relative to L5 Primary	Processing Gain Relative to L5 (dB)
2046 chip I Primary	2%	-7.0
10230 chip Q Primary	50%	0.0
40920 chip Q Intermediate	**200%**	**6.0**
10230 chip L5 Primary Code	100%	0.0

The Q channel intermediate code provides 6 dB more processing gain than the L5 signal for a factor of 2 increase in complexity relative to L5

*L = code length, Rc = chip rate

Data Message Structure

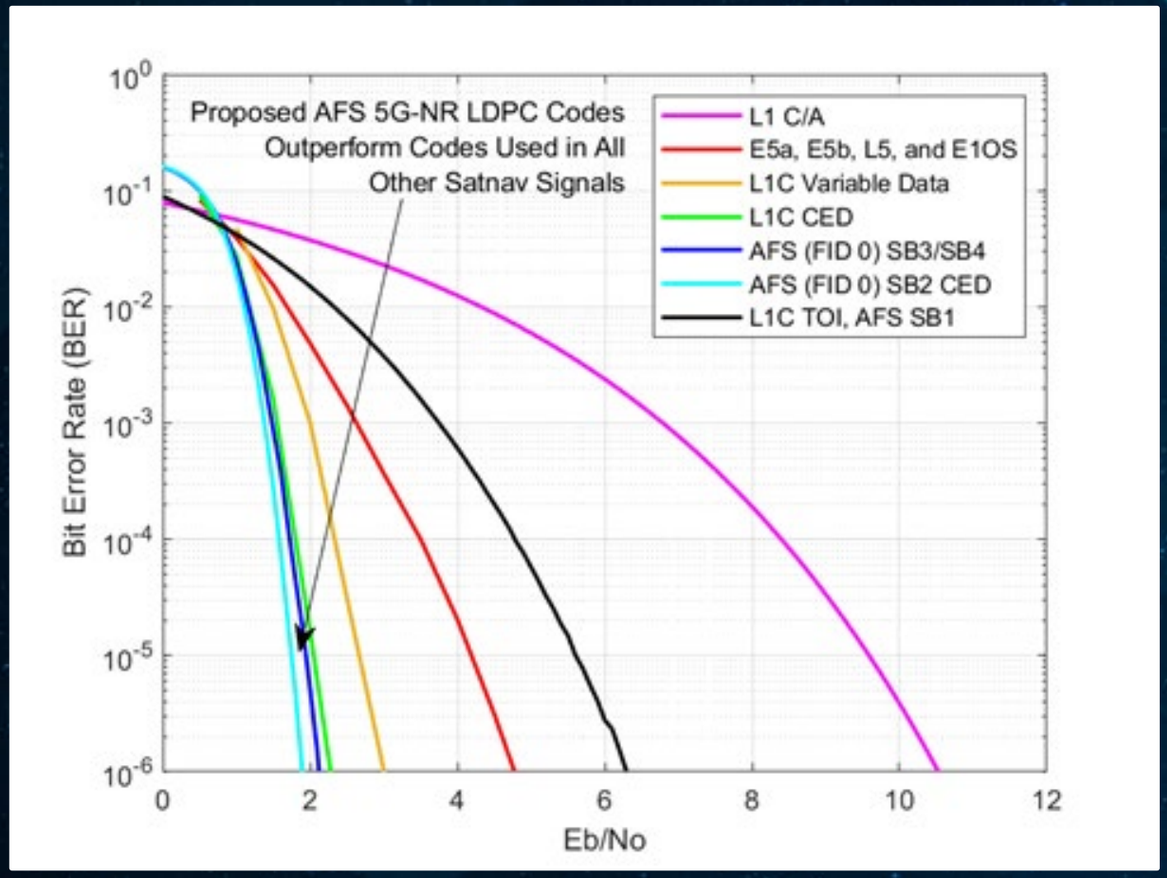
- The AFS Data message frame structure begins with a sync word for lightweight “data only” receivers.
- The structure was optimized to maintain the subframe block (SB) sizes as large as possible for future growth.
  - The 5G NR LDPC encoding was selected to leverage a commercial standard for the the forward error control coding design.

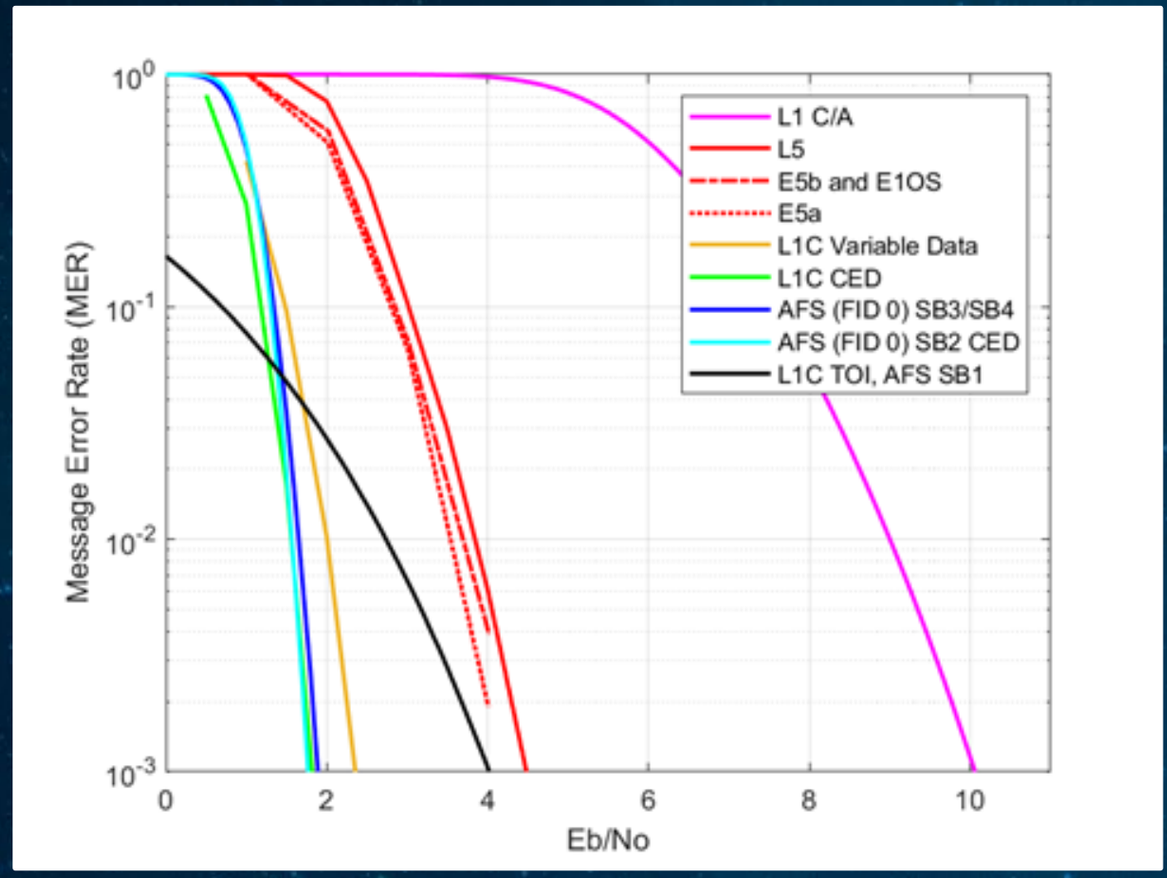


- 500 sps allows lunar providers frequent navigation message updates compared to Earth GNSS systems, with flexibility to maintain accuracy.
- In addition, other LunaNet information forwarded via message.

Data Message Performance

- Rate ½ LDPC codes were designed using methodology specified for 3GPP*,
- Exceeding performance of all other nav messages in terms of Eb/No.
- Balanced design with similar sensitivity target for sync, tiered code and data coding.
- CED combining further improves sensitivity.

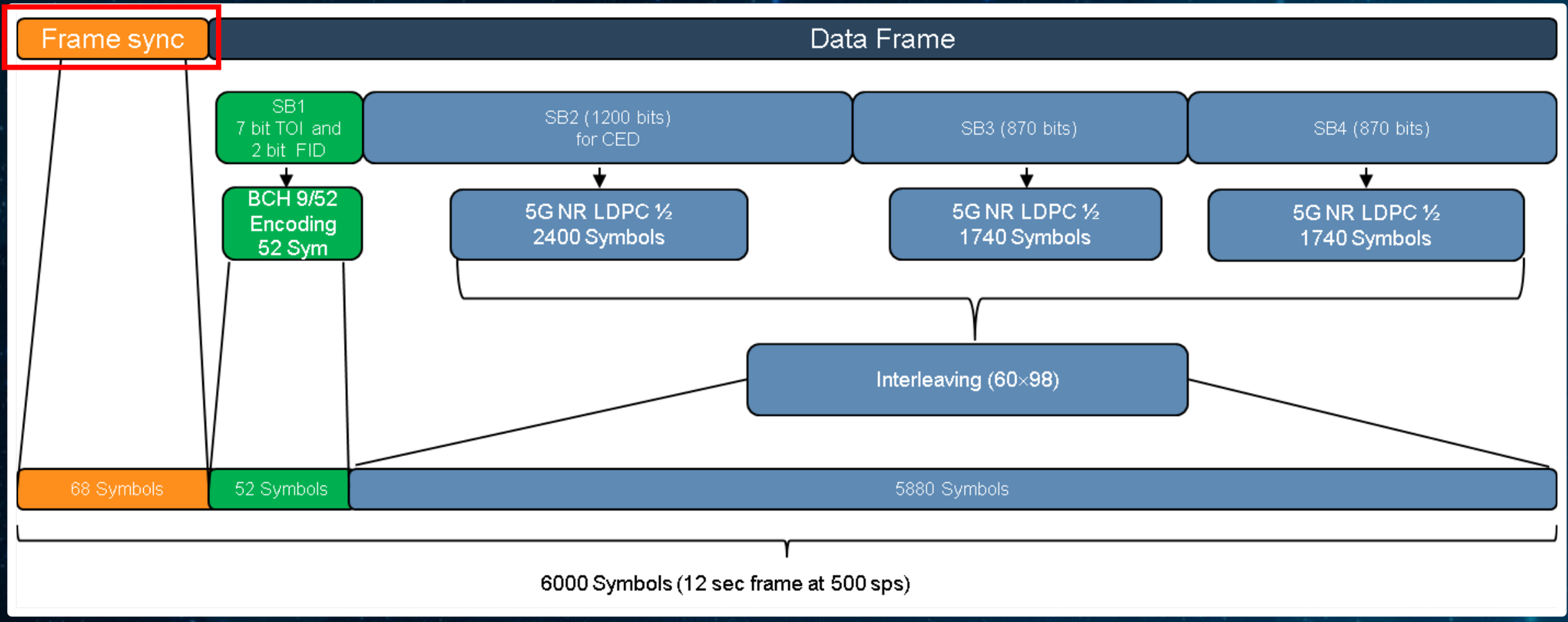




*3rd Generation Partnership Project (3GPP) (Jul. 2020). Technical Specification Group Radio Access Network; NR; Multiplexing and Channel Coding, Release 16, V16.2.0, 3GPP Standard TS 38.212.

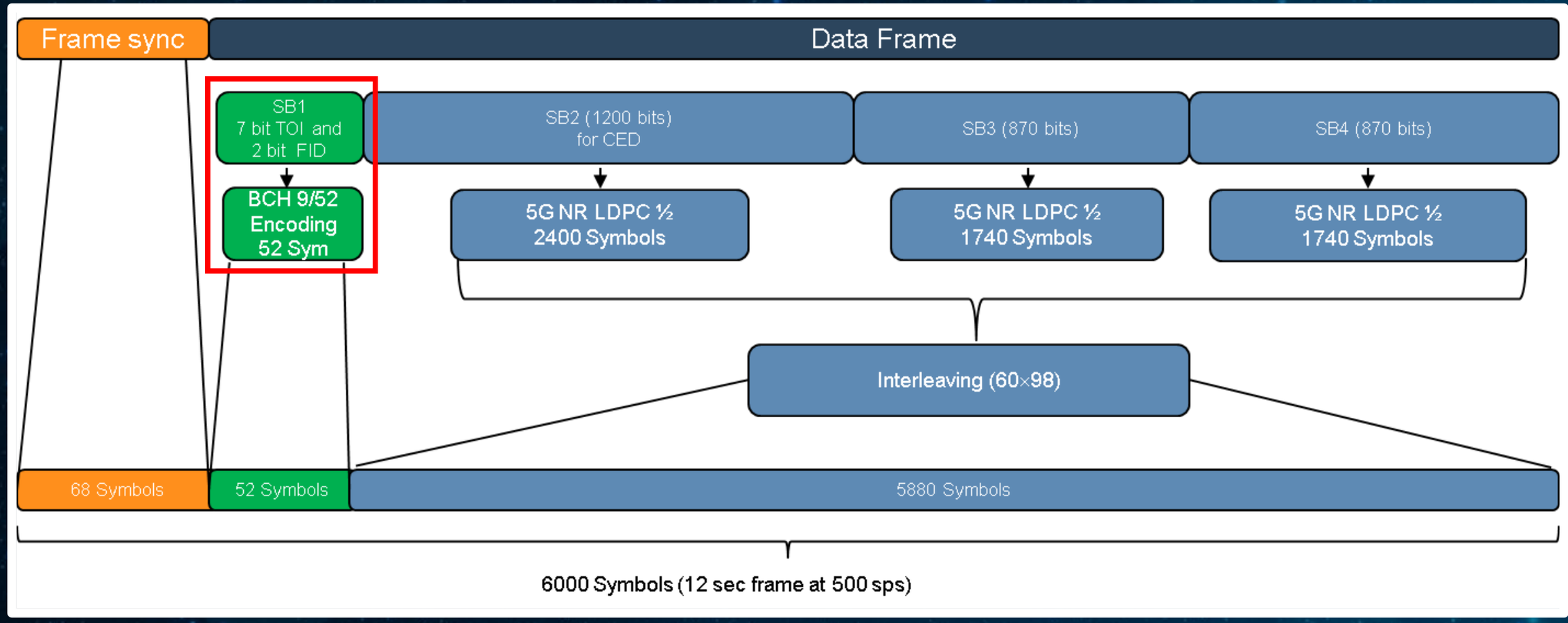
AFS Data Frame Sync.

- Frame sync of 68 symbols provides balance between No. symbols, C/N0 and data interleaver factorization



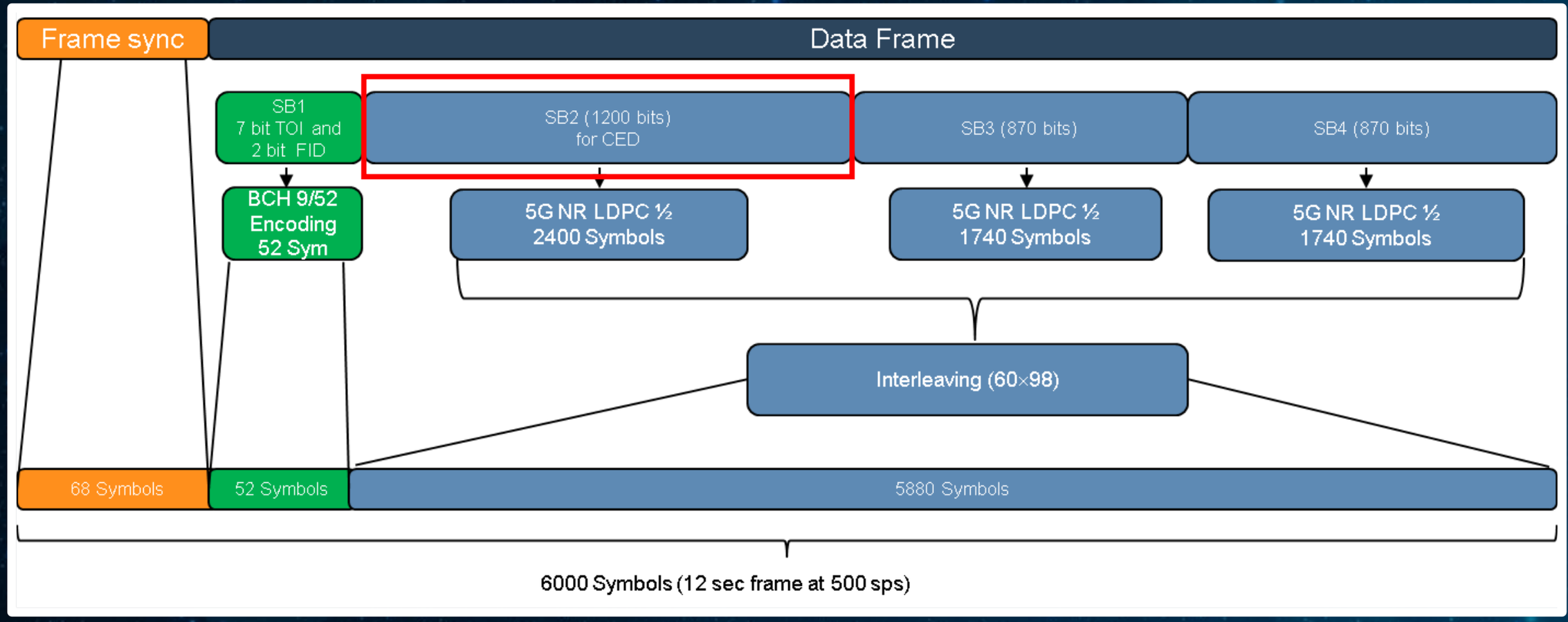
AFS Message (SB1)

- SB1 is composed of 9 BCH code bits.
  - 2 bits assigned to the frame identifier (FID), enabling future data frame structure flexibility (default FID = 00).
  - 7 bits are used for the Time of Interval (TOI) count over a 20 min interval.



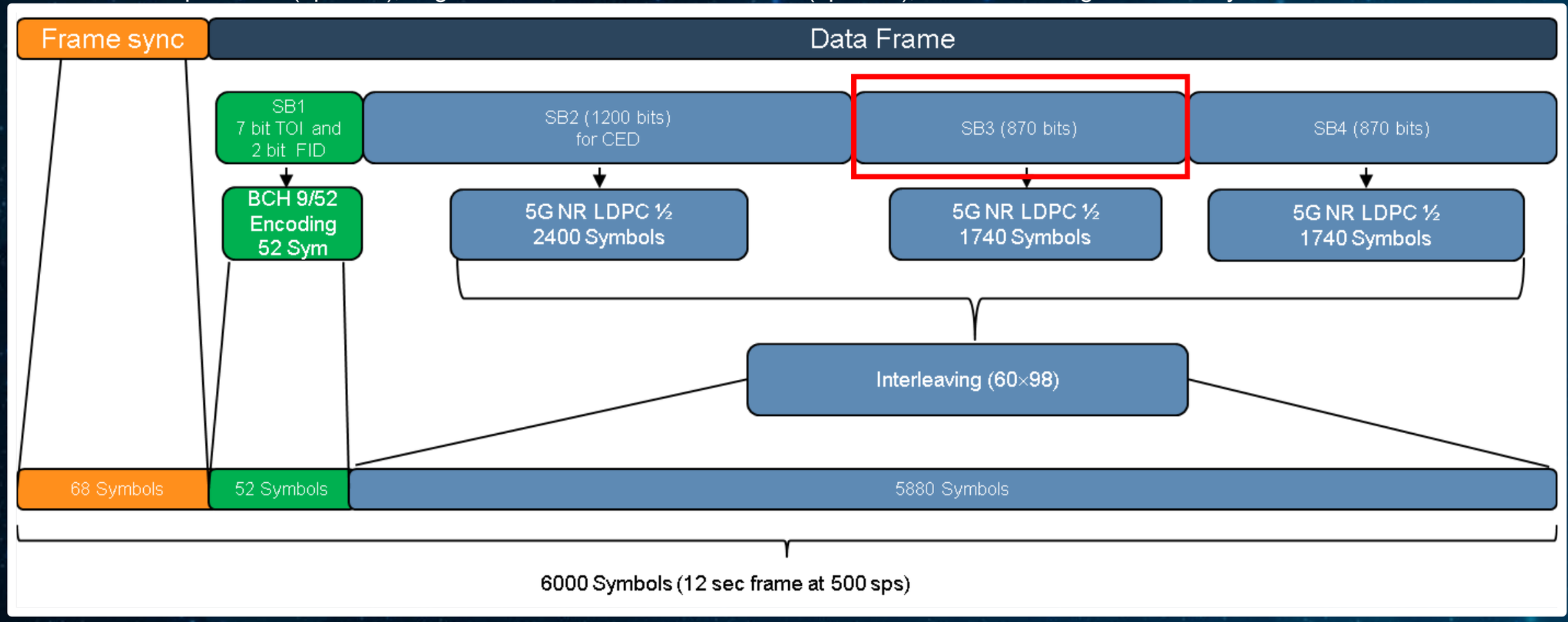
AFS Message (SB2)

- SB2 shall contain at least clock and ephemeris data (CED), time of transmission (ToT), health and safety, time conversions, and cyclic redundancy check (CRC)



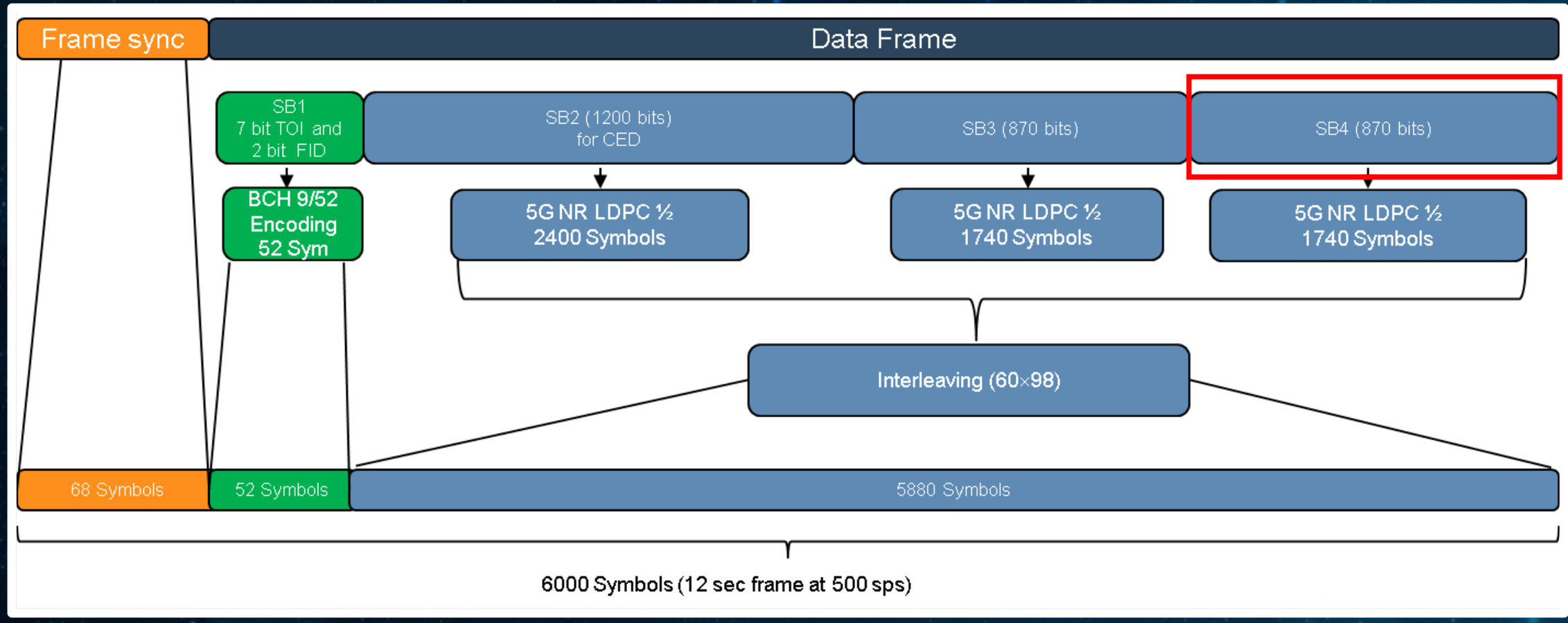
AFS Message (SB3)

- SB3 is a dynamic subframe that may be used for multiple purposes, including specific custom messages from the LNSP that are not specified in the LNIS AD1 (e.g., proprietary messages). Proprietary messages are not interoperable and require the LNSP to establish a SISICD for user implementation.
- SB3 shall contain multiple orbit almanac, coordinate frame conversions, multiple antenna properties (optional), maneuver (optional), single attitude state/ ephemeris (optional), augmentation differential corrections (optional), custom messages defined by the LNSP.



AFS Message (SB4)

- Similar to SB3, SB4 is also a dynamic subframe and shall contain LunaNet network access information, user schedule notice (information for Point-to-Point services), ancillary info (optional), custom messages defined by the LNSP.



Summary and Conclusions

- LunaNet's AFS was designed to provide an interoperable standard for future PNT services currently under development by NASA, ESA, and JAXA.

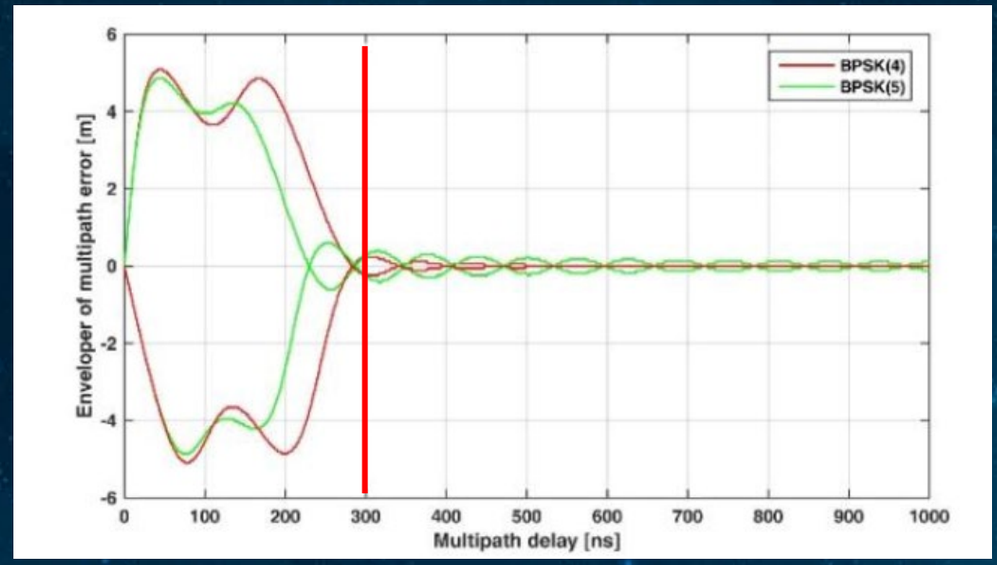
- The signal leverages lessons learned from terrestrial GNSS, and will service both high performance and low-SWaP users in the lunar vicinity.

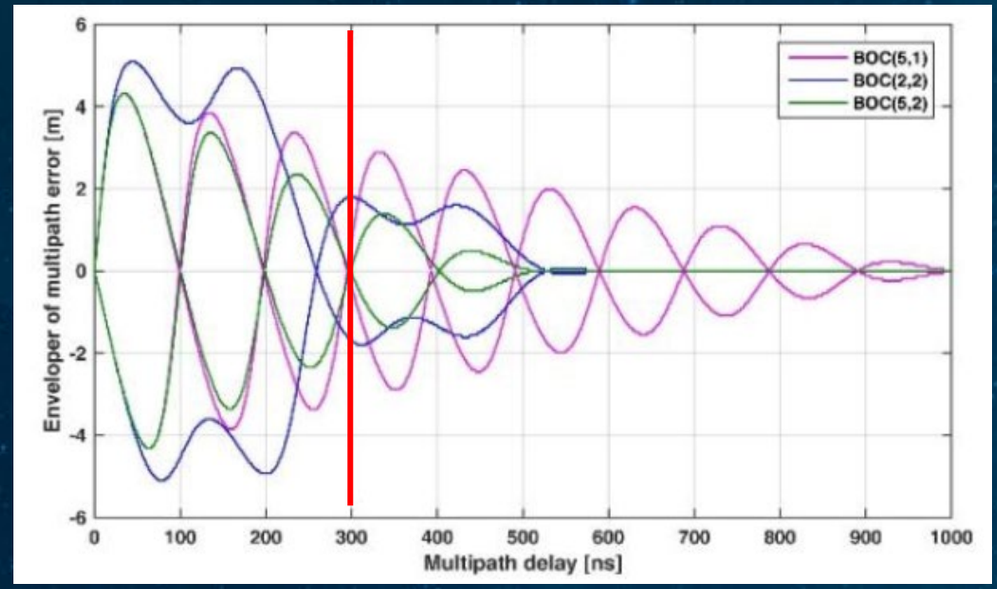
- The AFS provides several enhancements compared to other GNSS signals:
  - Employs 5G-NR Forward Error Control coding with the best decoding performance of any GNSS signal.
  - Three-tiered ranging codes permit receivers to trade acquisition complexity with sensitivity.
  - Tertiary overlay code that enables rapid time dissemination, high integrity code acquisition, and frame Sync.
  - A high integrity data sync word is provided to enable low-SWaP single-channel decode data without a pilot overlay.
  - The signal structure also supports future changes through the robust BCH encoding of the FID field without sacrificing the ability to improve data message performance using CED combining.
  - Overall, the AFS provides ample flexibility and performance by accommodating a range of use cases and operational modes.

Backup

Multipath Performance

- Multipath Error Envelope (MEE)
- General Trends are similar
- BPSK is affected until ~300 ns
- BOC is affected until ~500-800 ns

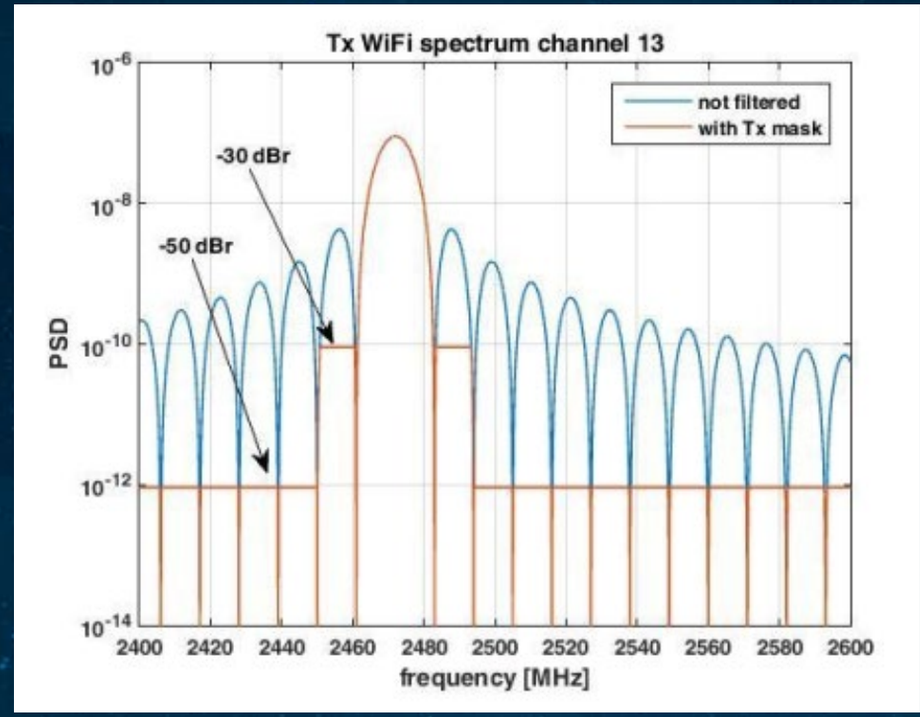




WiFi Interference

- Impact of WiFi on different AFS Modulations
- Assuming WiFi DSSS modulation (in channel 12/13)
- Implementing WiFi 801.11 transmission mask

- **BPSK(5)** shows lowest impact for **channel 12**



C/N_0	WiFi ch.	Spectrum mask	BPSK(4)	BPSK(5)	BOC(5,1)	BPSK(1) (data channel)
27 dB/Hz	12	On	87.3	86.4	76.2	90.1
		Off	63.1	63.2	64.1	62.2
	13	On	73.7	74.0	75.8	73.4
		Off	62.4	62.1	59.0	63.6

Data Message Design Tradeoff

- Select a sync word length that met the desired performance of L1C's Rate 9/52 BCH code (25 dB-Hz), and I channel carrier tracking thresholds.
  - Constrained by Interleaver factorization, C/No performance and data utilization

$$\frac{E_b}{N_0} = 5.61 \text{ for BER =1E-05} \Rightarrow \frac{C}{N_0} = \frac{E_b}{N_0} + 10\log_{10}\left(500\,\frac{sym}{sec} \times \frac{9}{52}\frac{bits}{sym}\right) = \mathbf{25\ dB\ Hz}$$

Sync Word Length (Symbols)	Min. C/N_0 (dB-Hz)	Number of data Symbols Remaining	Interleaver Factorization		Rational
			Rows	Columns	
52	27.41	5896	67	88	Requires high C/N_0
64	25.69	5884	1471	4	Poor Factorization
68	25.23	5880	60	98	Best Balance
128	21.16	5820	56	103	Too many Symbols

- 68 Symbol provides the best balance between No. of data symbols, C/N_0 and interleaver factorization.
- Two out of 9 BCH code bits are assigned to the FID, permitting the flexibility to change the data frame structure in the future, with the default structure identified by FID = 00.
- The remaining 7 bits are used for the TOI count over a 20 min interval in which the CED data is unchanged.

*Assumed sync word detection and false alarm probabilities: P_d = 0.99 and $P_{fa} = 10^{-6}$

CED = Clock and Ephemeris Data