LORAN-5G

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Abstract

In this paper we propose a radically new signal design, LORAN-5G, that can be used by legacy LORAN-C stations in support of the National Timing Security and Resilience Act. The Timing Reference Signal, TRS, is based on similar OFDM reference signals found in 3GPP Release-16 for 5G-NR positioning. TRS has built-in orthogonality to protect against near-far issues, and it is robust against in-close ionospheric multipath. Furthermore, the signal has modest requirements for XO accuracy, yet can support high user speeds. The signal structure has 2-3 orders of magnitude lower requirements for peak power of transmission compared to legacy LORAN-C pulses. This feature can reduce capital expenditures for power amplifiers as well as reduce annual cost of operation through reduced power consumption. Finally, LORAN-5G includes the design for an integrated data channel with raw data rate of > 2.6 kbps per station. This data channel can be used for broadcast of station location, reference time and correction data to make LORAN-5G a truly independent timing and navigation system.

Background

National Timing Security and Resilience Act

The National Timing Resilience and Security Act (NTRSA) was introduced with bi-partisan support in the US senate in 2017, and it was later signed into law by the President as part of the Frank LoBiondo U.S. Coast Guard Authorization Act of 2018 (sec. 514). The bill was in response to widely recognized risks in over-reliance of GPS for critical infrastructure and other use cases with stringent resiliency requirements.

The primary aim of the bill was to provide a resilient backup system to provide accurate timing independent of GPS. Several key features were spelled out, it must be: wireless, terrestrial, have wide-area coverage, be extremely resilient and difficult to disrupt or degrade, work deep indoors, be developed\operated by private industry, and be capable to expand to include position\navigation.

The original bill had language that called for the reuse of LORAN-C resources. After a review process, the bill was broadened to allow consideration of other options. The U.S. Department of Transportation (DoT) asked private industry to apply to be considered and various technology vendors brought their solutions to be considered including technologies such as: Low-Earth Orbit satellites, a beacon system, fiber optic timing, Wi-Fi, and inertial sensors. The DoT is currently evaluating the readiness and suitability of the various candidate technologies.

LORAN-C

Is a low frequency (100 kHz) positioning\timing system that uses hyperbolic navigation methods to provide position and time. It was primarily used by maritime users and was widely available in the Atlantic and Pacific oceans across the coasts of North America, Europe and Japan. Today countries such as China, Russia and South Korea continue to operate Loran-C systems and along with others are actively discussing upgrading and increasing capabilities of their Loran systems. The Loran-C signal has been implemented with very high power (up to 4 MW) by transmitters using very tall antennas (typically 200m) with corresponding coverage areas oftentimes beyond 1000 km.

5G-NR

3GPP Release-16 (Rel-16) introduced positioning features to 5G-NR (New Radio). 5G applies OFDM signal structures both for uplink from User Equipment (UE) and downlink from gNodeB (gNB aka “base station”). 3GPP standards documents (3GPP, PHY, 2020) describe the downlink Positioning Reference Signal (DL-PRS). DL-PRS has several options for comb and symbol combinations, and the various options can support different numbers of sets of transmitters with full orthogonality form each other. Orthogonality is a key performance indicator for terrestrial positioning systems whose operation may be obstructed by near-far issues.

Rel-16 (3GPP, LPP, 2020) also introduces support for several measurement methods:

- Downlink Time-Difference of Arrival (DL-TDOA)
- Uplink Relative Time of Arrival (UL-RTOA)
- Multi-cell Round-Trip-Time (MC-RTT)
- Enhanced Cell Identity (eCID)
- Uplink Angle-Of Arrival (UL-AoA)
- Downlink Angle-of-Departure (DL-AoD)

Only DL-TDOA is of interest here because it is a downlink-only method, i.e. broadcast, and it requires a well-synchronized network of transmitters to achieve good operational performance. The other methods either rely on use of uplink signals or rely on use of different beams of transmission. A 100 kHz system can assume neither use of uplink (user antenna size and power constraint) nor use of transmit beams (legacy LORAN-C sticks are omni-directional).

Finally, Rel-16, also in 3GPP LPP, describes options for UE-Assisted (UE-A) and UE-Based (UE-B) positioning methods. The former requires UEs to receive assistance data with signal identifiers and search spaces and for the UE to report measurements to a location server for position determination. Since no LORAN-5G dependent uplink would be available, and following the spirit of resilience, a UE-B approach would be needed for the proposal at hand. UE-B would require a broadcast data link with information about station location, time-base with corrections and other pertinent information that would enable a user to operate with complete independence from other systems. Fusion with other systems would of course be feasible, but not required.

Physical layer signal design for LORAN-5G

Design goals and constraints

We chose to use the following high-level design considerations for the physical-layer design.

- Support the same frequency allocation and spectral mask as the original LORAN-C pulses
- Support for the same coverage area as the original LORAN-C pulses
- Robustness against multipath
- Robustness against near-far problems

- Robustness against interference
- Low capital equipment cost and low operation cost
- Support for a data channel

Frequency allocation and spectral mask

LORAN-C stations operated using a 100 kHz carrier modulated by repetitive trains of shaped pulses. The frequency BW allocation is 20 kHz, with a requirement that 99% of the signal energy needs to be within ± 10 kHz of the 100 kHz center frequency. This means that the total out-of-band emission can be as high as -20 dB w.r.t. the in-band transmitted power.

Coverage area

Some LORAN-C stations supported transmission power in excess of 1 MW, and these stations had coverage areas in excess of 1000 km. The propagation conditions of the ground wave generally improved with moisture content and increased salinity.

Multipath robustness

The ionosphere is the main source for multipath for LORAN-type systems. The ionosphere typically varies throughout the day and it is driven by solar illumination and activity. The height of the ionosphere is generally considered to be in the range of 50km to 1000km. We can estimate the delay from a single-hop ionospheric reflection as a function of the Earth radius, the ionosphere height and the downrange distance using Figure 1.

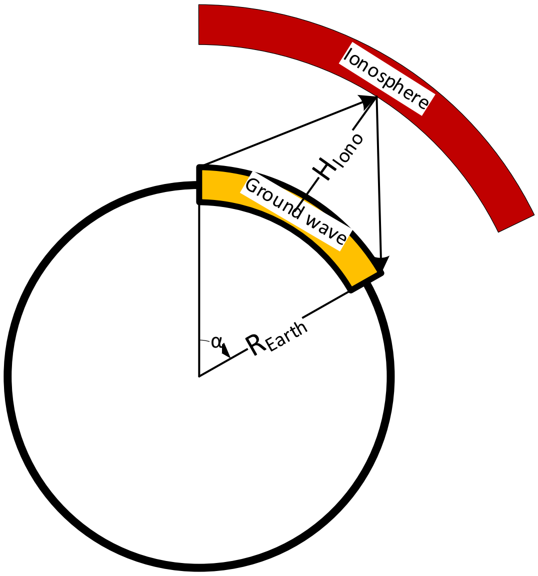

Figure 1 Excess ionospheric delay estimation

The downrange distance can be expressed as:

$$d_{GroundWave} = \frac{2 \cdot \pi \cdot \alpha \cdot R_{Earth}}{360} = \frac{\pi \cdot \alpha \cdot R_{Earth}}{180}$$

α is the central angle, in units of degrees, between the transmit station and a receiver.

R_{Earth} is the radius of the Earth, which is approximately 6371 km.

The one-way delay from a transmit station to the ionosphere, or the one-way distance from the ionosphere to a receiver can be expressed by the law of cosines.

$$d_{iono\_one\_way}^2 = R_{Earth}^2 + (R_{Earth} + H_{Iono})^2 - 2 \cdot R_{Earth} \cdot (R_{Earth} + H_{Iono}) \cdot cos\left(\frac{\alpha}{2}\right)$$

$d_{iono\_one\_way}$ is the one-way distance to or from the ionosphere.

H_{Iono} is the ionosphere height.

We can parametrize the second equation by downrange distance by using the first equation.

$$d_{iono\_one\_way}^2 = R_{Earth}^2 + (R_{Earth} + H_{Iono})^2 - 2 \cdot R_{Earth} \cdot (R_{Earth} + H_{Iono}) \cdot cos\left(90 \cdot \frac{d_{GroundWave}}{\pi \cdot R_{Earth}}\right)$$

Thus, the difference between the skywave delay and the groundwave delay is as follows:

$$\begin{aligned} excess\_delay_{multipath} \\ &= 2 \cdot \sqrt{R_{Earth}^2 + (R_{Earth} + H_{Iono})^2 - 2 \cdot R_{Earth} \cdot (R_{Earth} + H_{Iono}) \cdot cos\left(90 \cdot \frac{d_{GroundWave}}{\pi \cdot R_{Earth}}\right)} \\ &- d_{GroundWave} \end{aligned}$$

Figure 2 shows a plot of the equation above for a few examples of ionosphere heights. Note that the curves are limited to non-negative elevation angles.

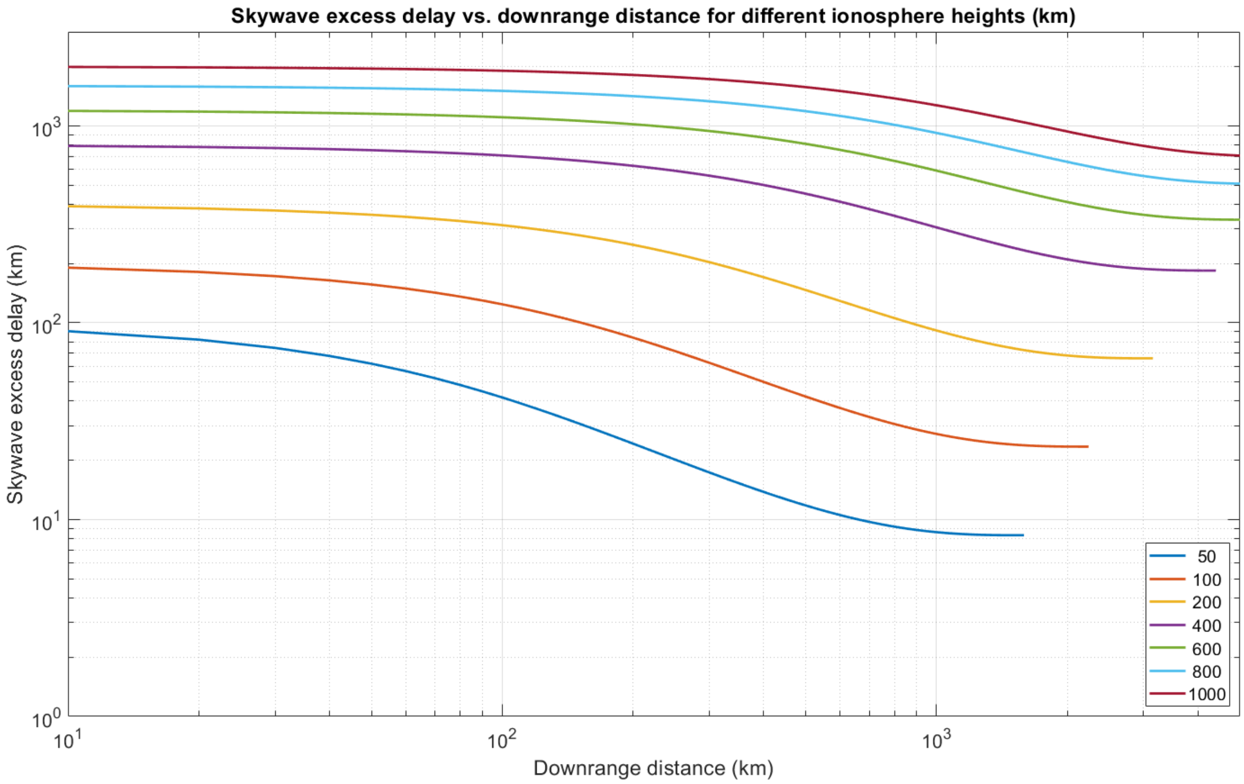

Figure 2 Skywave delay vs groundwave as function of downrange distance for different ionosphere heights

Equipment cost and cost of operation

Peak-to-Average-Power Ratio, PAPR, is a critical parameter for the requirements for high-power amplifiers. Class-A and class-A/B linear amplifiers typically require significant back-off (~10 dB) to avoid saturation. These classes of power amplifiers burn an almost constant amount of power irrespective of transmitting a signal or not. Furthermore, power amplifier cost tends to increase monotonically with power output. Minimizing the PAPR not only minimizes the capital equipment cost, but it also minimizes the cost of operation through reduced power consumption needs.

Near-far problem

Pseudorange and range-based RF positioning and navigation systems require use of measurements from multiple transmission sources for solving the required number of unknowns in the navigation equations. While a user of a timing system, could operate using only a single transmission source if their position is known, use of multiple measurements would enable cross-checking for improved confidence in the timing solution.

Unlike communication systems, position, navigation and time (PNT) systems require (or at the very least desire) collection of a multitude of concurrent measurements from multiple sources. As such, it would be imperative that the signals received from different transmitters are detectable concurrently and in the presence of each other. This is particularly important for terrestrial systems where there may be a considerable difference in the proximity to the closest and the farthest transmission stations. Such signals may have enormously different received power levels.

Interference robustness and availability

Lightning is the most significant natural interference source for LORAN-type systems. While near-far problems can be alleviated through signal design and deployment planning, lightning is a broad-band interference source that can be several orders of magnitude stronger than LORAN-type signal. Clever receiver design (C. O. Lee Boyce Jr, 2007) can substantially improve operation in the presence of lightning, but from a signal design standpoint it would be advantageous to minimize the observation interval required for operation as well as providing a near continuous stream of observation windows. In this way, a lightning strike could impact one observation window, but the next observation window may be unaffected.

Data channel

From an end-to-end systems perspective it would be advantageous for a user to be able to operate fully in stand-alone mode, like GPS. This means that all the required information needed for generating a time fix or a positioning fix would be available from observing the LORAN-5G signal itself. Such operation would require broadcast of the station location (like GPS ephemeris), clock correction models and an absolute time reference (like GPS z-count). However, a data-channel could be expanded to carry differential corrections as well as authentication information. eLoran have similar correction broadcast capabilities (Gerard Offermans S. B., 2016), (Gerard Offermans E. J., 2014), and Loran has been proposed for broadcast of GPS integrity information as well (Lo, 2002).

Timing Reference Signal

We propose using an Orthogonal Frequency Division Multiplexed (OFDM) scheme as basis for broadcast signal design. While variants of Code-Division Multiple Access (CDMA) are the signal design of choice for space-based satellite positioning systems that do not suffer from near-far issues, OFDM schemes have found plentiful use in terrestrial positioning systems, like 5G-NR, 4G-LTE and Wi-Fi.

OFDM background

At the atomic level, OFDM schemes are defined by a Resource Element, RE. A resource element consists of the contiguous transmission of a sine wave with a certain amplitude, frequency and initial phase for a brief time period. Different REs can be assigned to different sub-carriers in frequency domain, and different symbols in time-domain. The spacing between REs in frequency domain is referred to as the Sub-Carrier Spacing, SCS, and this is generally inversely proportional to the symbol duration. At a molecular level, a set of REs can be combined into a Resource Block, RB. Resource Blocks typically consists of a dozen sub-carriers and the RBs span about a dozen time symbols. The RBs can be stacked on top of each other in frequency domain to fill up an allocation of bandwidth.

One RB's duration is often referred to as a *sub-frame*, where a *frame* is a collection of 10 contiguous sub-frames. In NR, a sub-frame may consist of one or more slots, which themselves consist of 12 or 14 symbols. In LTE and NR, a collection of frames are enumerated and a particular frame can be identified by its Sequence Frame Number, SFN. In the previously mentioned systems, SFN has a range of [0, 1023] and SFN repeats on 1024 frame-boundaries thereafter.

Inter-symbol interference (ISI)

OFDM in practical use for communications apply a cyclic pre-fix, CP, to avoid inter-symbol interference, ISI. The CP is generated by taking the tail end of the source symbol and pre-pending it to the source symbol. The CP needs to be larger than significant multipath delays of the channel. In the case of LORAN-type systems, the ionosphere is the main driver of delay spread, and the worst-case multipath delay is 2000 km for a 1000km ionosphere height, so CP length should be larger than 2000 km.

Inter-carrier interference (ICI)

Since OFDM systems interleave frequency content among different sub-carriers, a network of transmitters needs to be steered to a common frequency reference to avoid inter-carrier interference among different stations. Typical frequency accuracy requirements for cellular systems range from 50 ppb to 250 ppb, which is sufficient for communication operation. Note that for a 100 kHz center frequency, 50 ppb corresponds to 1e5 Hz*50e-9 = 5e-3 Hz = 5 milli-Hertz.

An RF-based timing and navigation system would naturally require excellent accuracy and great long-term stability in the determination of time of transmission, and by corollary also outstanding accuracy in frequency.

OFDM parameters for LORAN-5G

We propose basing LORAN-5G on OFDM signal structures found in 5G-NR.

CP

NR has options for normal CP (NCP) and extended CP (ECP) where the former uses 14 symbols per slot and the latter uses 12 symbols per slot. NCP has a CP ratio of 144/2048 or 320/2048 (first symbol only) depending on the symbol index and ECP has a CP ratio of 512/2048 for all symbols.

We recommend using a signal structure with 15 Hz SCS, and we can define a basic LORAN-5G time unit.

$$T_s = \frac{1}{15 \cdot 2048}\ seconds$$

The net symbol duration (w/o CP) is 2048*T_s. Following the NR convention, for NCP the CP duration is 144*T_s or 320*T_s which corresponds to approximately 1405 km and 3122 km respectively. The NCP option doesn't generally guarantee CP less than the maximum skywave delay, so they would not meet ISI requirements. However, ECP has a CP-length of 512*T_s = 4997 km which is significantly longer than the maximum skywave delay. Use of the ECP option would be required to meet ISI requirement.

ECP allows 12 symbols per sub-frame, and a LORAN-5G RB consists of 12 sub-carriers. Each symbol including CP lasts ~83.3 ms, a sub-frame lasts 1 second exactly and a frame lasts 10 seconds precisely. Note that the symbol duration falls squarely in the middle of the ~60-100 ms Group Repetition Interval (GRI) range of past LORAN-C deployments.

Resource block

We propose interleaving time/navigation reference symbols with data symbols. Decoding of data resource element requires an anchor reference signal with known reference amplitude and known reference phase. Thus, we recommend using pairs of reference symbols followed by data symbols. Furthermore, we propose using a comb-6 symbol structure, with a one-to-one match for sub-carrier allocations in reference/data symbol pairs. A comb-6 symbol structure supports up to 6-times power boosting (~ 8 dB) of symbols because only every 6th sub-carrier is in use.

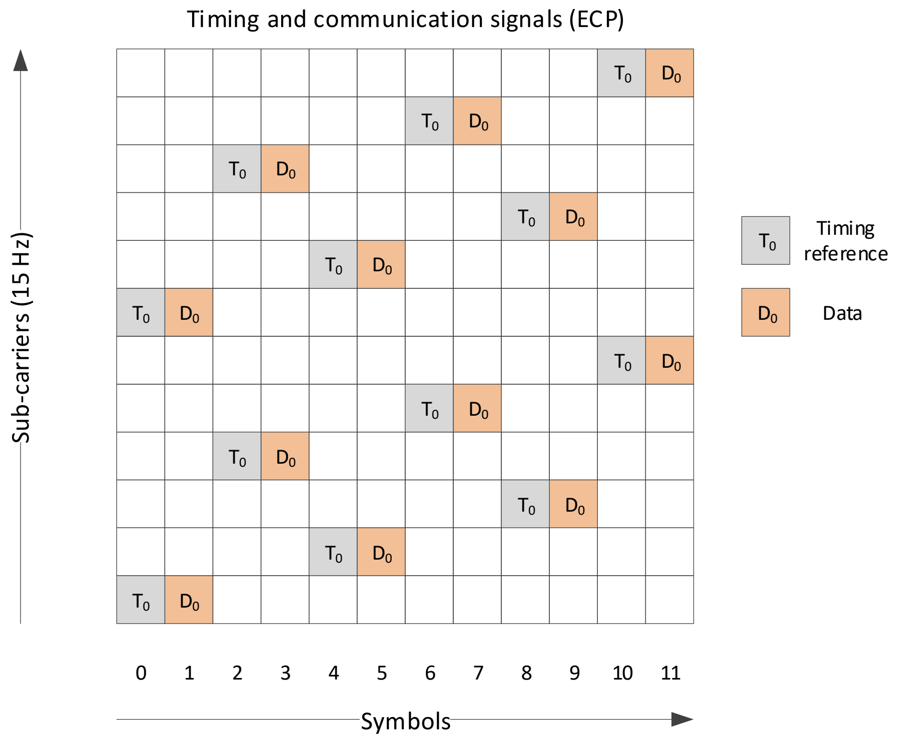

Figure 3 LORAN-5G RB with reference and data symbols

Note that the RB in Figure 3 supports a full frequency spectrum if all reference symbols are combined coherently. Any holes in the frequency spectrum in an RB would repeat in other RBs, and as such would manifest itself as aliases in a corresponding time-domain correlation peak. The seemingly random ordering of frequency offsets of sub-carriers in the different symbols is meant to minimize the impact of such time aliases should one or more symbols be unavailable for coherent integration, e.g. from lightning interference.

Modulation scheme

We suggest utilizing Quadrature Phase Shift Keying, QPSK, modulation for both reference and data symbols. QPSK allows for direct re-use of the 5G-NR Gold-code generator and allocation method for the reference signal.

Large-scale time

With 10 second frame lengths, it would be suitable to represent time-of-week, TOW, in 10 second increments. LORAN-5G TOW would have a range of [0, 60479], which would fit nicely into 2 bytes of data. Similarly, using 2 bytes to represent week numbers would support more than 1260 years of range before the first roll-over. Otherwise, care should be taken to align/relate LORAN-5G time with GPS time, so the two systems could be used interchangeably and seamlessly.

Bandwidth

LORAN-C operated in a dedicated band with 20 kHz of total BW around 100 kHz, i.e. [90, 110] kHz. Note that this technically qualifies LORAN as an ultra-wideband, UWB, signal as its fractional bandwidth is 20%.

Legacy LORAN-C pulses were required to keep 99% of the total transmitted signal energy within the [90, 110] kHz band. This means that 1% or -20 dB of out-of-band transmission was allowable. In the pre-cursor to NR, LTE had BW options for up to 100 RBs. However, for LORAN-5G we could crank up the number of RBs to one hundred and eleven, and still meet the -20 dB out-of-band emission mask.

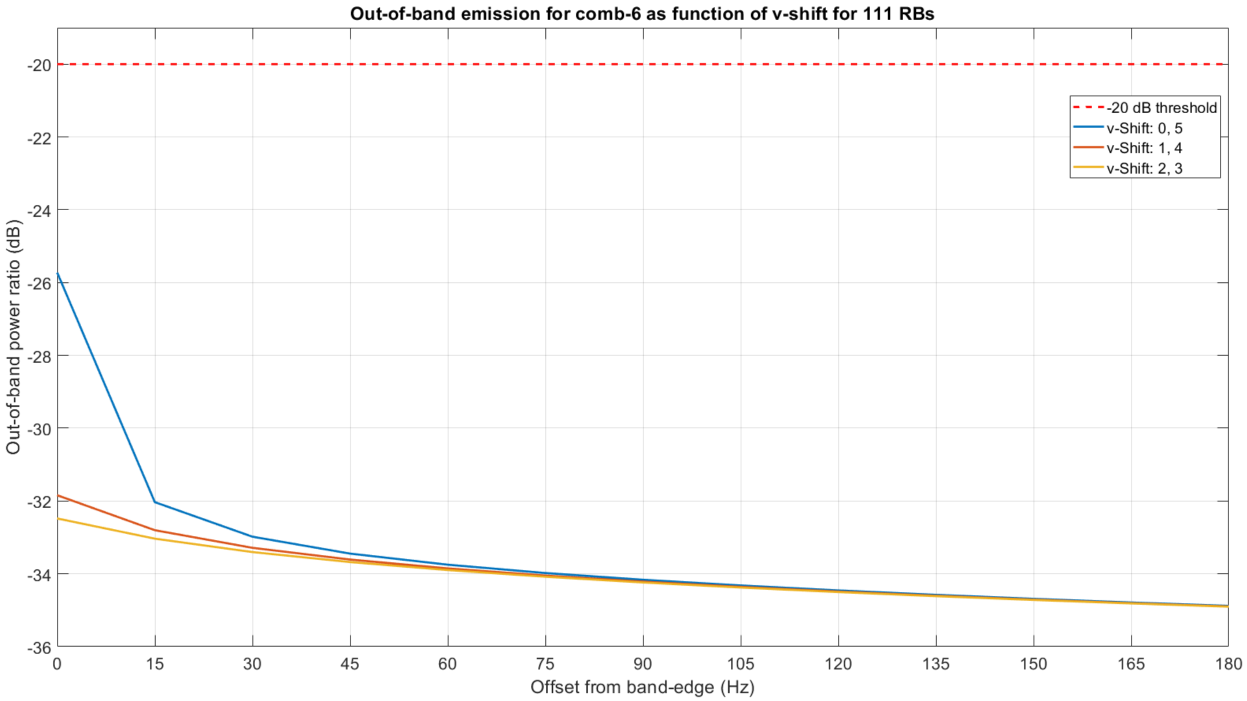

Figure 4 Out-of-band emission profile for 111 RB BW option

Data channel

With data symbols also using a comb-6, it would allow for the same 6x power boost as for TRS symbols. Using QPSK modulation would allow each data RE to carry 2 bits of information. For a BW option with 111 RBs, in one second there would be 111*6*2 = 1,332 data REs. Thus, the raw data rate capacity of each station would be 1,332*2 = 2,664 bits/second. Since comb-6 systems allow for up to 6 orthogonal groups of stations, the full system capacity would reach 6*2,664 bits/sec = 15,984 bits/sec. Higher order modulation schemes, such as 64-QAM, could increase the data channel throughput, but at a cost of shortening the range of detection.

Performance simulation

Time-of-arrival estimation

Classical LORAN-C receivers would attempt to detect the 3rd zero crossing at 9km from the start of the pulse. A low ionosphere height of 50 km produces a reflection with excess delay of 9km at a downrange distance of ~ 800 km.

Figure 5 shows auto-correlation functions of a TRS option with 111 RBs. The top sub-plot shows the full-frequency a-corr function that results from coherently combining the 6 TRS symbols in a sub-frame. The red dashed line shows the a-corr function that results from processing only one TRS symbol. Since each symbol only has frequency content in every 6th sub-carrier, the holes in the frequency spectrum result in 6 time-domain alias peaks, spaced about 3331 km apart. Note that if a receiver location is known with an accuracy better than +/- 1666 km, then such measurement ambiguities can be resolved.

While there's an SNR cost in using only a single symbol vs. coherently combining 6 symbols, single-symbol operation would allow for unique measurement opportunities every 1/6 seconds or ~166.7 ms. This could provide valuable during a lightning storm where only ~ 83 ms of clean observations would be needed for operation, compared to ~ 917 ms needed for full comb-6/6-symbol coherent processing. Some level of clock stability may also be needed to provide hold-over between observations.

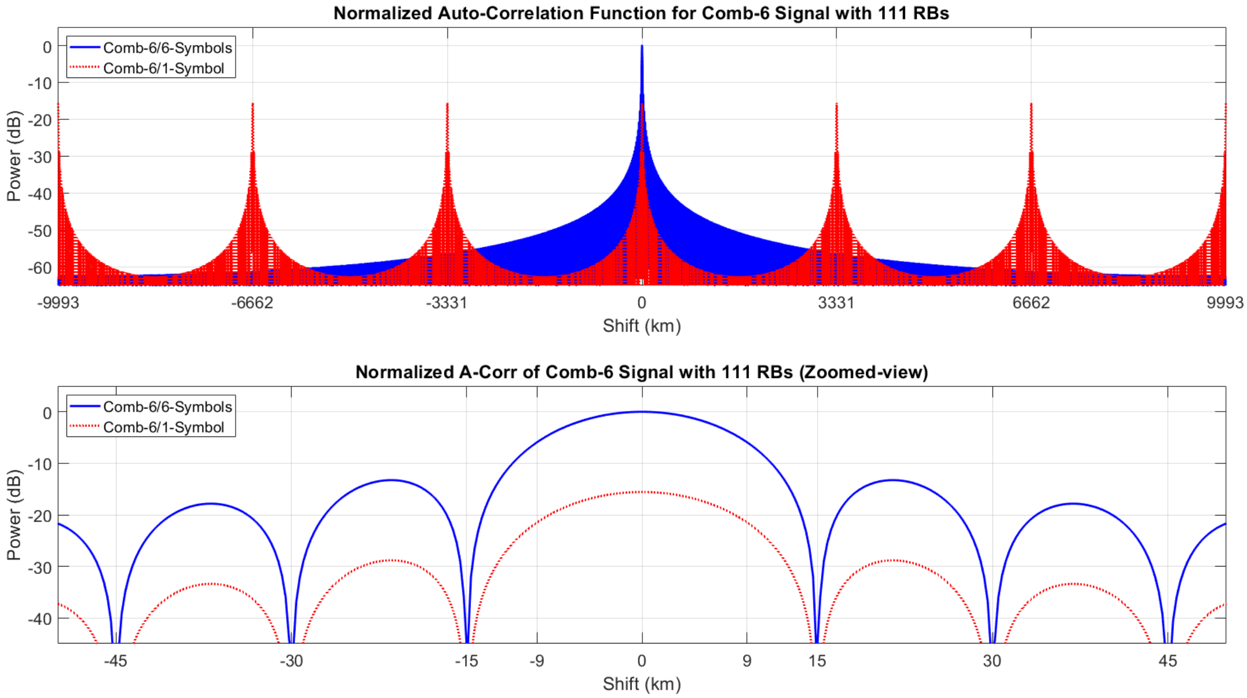

Figure 5 Auto-correlation function for TRS

The bottom sub-plot in Figure 5 shows a zoomed-in view around the main lobe of the auto-correlation function. The main lobe falls off by ~ 6dB at an offset of 9 km, and this will offer some protection from ToA estimation errors due to low ionosphere reflections.

Peak-to-Average Power ratio

We ran Monte-Carlo simulations for 1,000 sub-frames, each with 12 symbols. For each symbol we generated all 6 v-shift options and applied randomized QPSK modulation, and then calculated the PAPR. Figure 6 shows a CDF curve of PAPR from the Monte-Carlo simulations in blue.

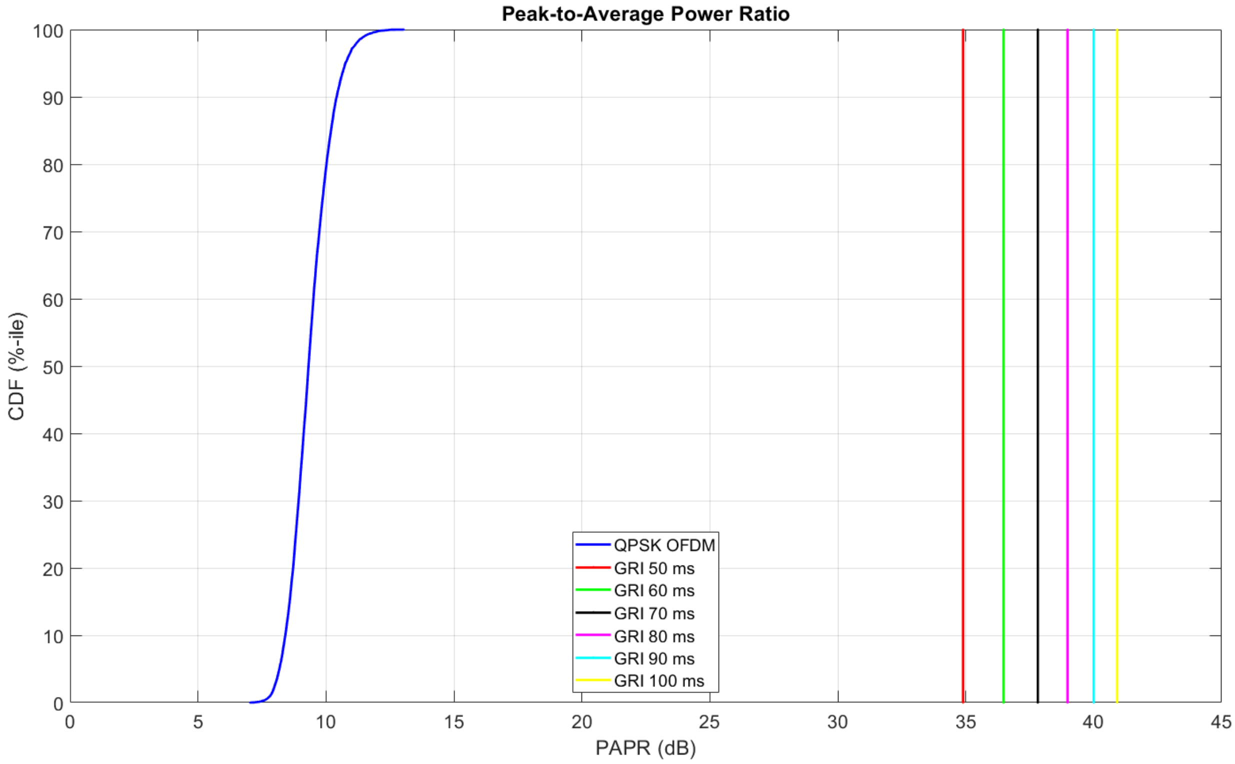

Figure 6 PAPR for QPSK and LORAN-C pulse-trains with different GRIs

Furthermore, we estimated PAPR for LORAN-C pulses for different Group Repetition Intervals (GRI) by approximating each of the 9 total pulses by a triangle wave with 200 µsec duration and dividing by the GRI. OFDM QPSK modulation falls around 10 dB of PAPR, while LORAN-C pulses range from 35 dB to beyond 40 dB for a GRI range of 50 ms to 100 ms respectively. This means that a QPSK modulated OFDM signal with 111 RBs can relax the PAPR, and by that the PA requirements, by 25-30 dB compared to legacy LORAN-C pulse modulation. In practical terms, this means going from the order of MW to the order of kW of peak RF power for the same average received power.

Error sensitivities

Inter-carrier interference

With a well-synchronized network of stations, the impact from ICI for nominal network operation is expected to be completely insignificant.

Coherent integration

A user that wishes to utilize a LORAN-5G service to its fullest extent would be required to acquire and coherently combine TRS symbols over approximately 1 second of duration. A user may have an inaccurate clock and/or be in motion. Due to the low center frequency, the absolute impact from Doppler, Δf, is also typically low.

$$\frac{\Delta f}{f_0} = \frac{\Delta v}{c}$$

Δf is the Doppler frequency offset.

f_0 is the center frequency.

Δv is user speed.

c is speed of light.

Conversely, due to the long wavelength, even significant user motion across the integration period may have a moderate impact on a correlation peak constructed from TRS symbols spaced across nearly 1 second.

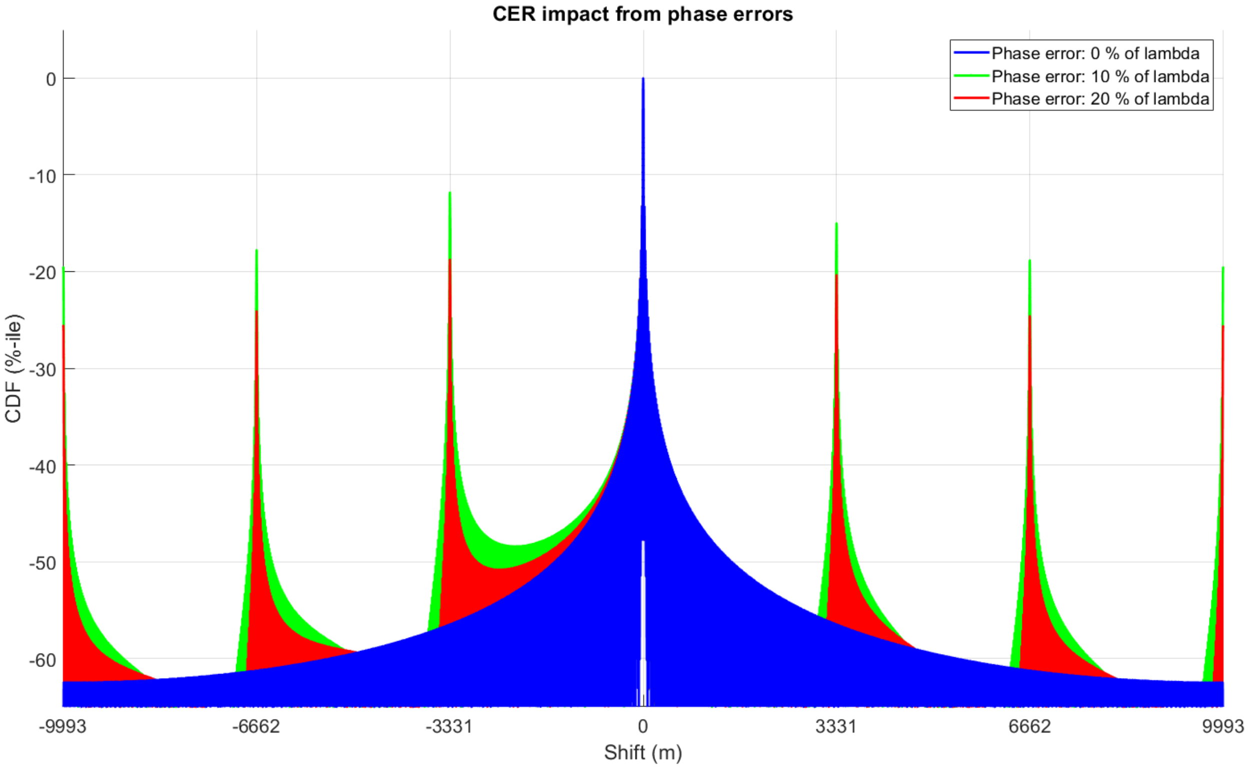

Figure 7 Phase error impact on coherent integration

Figure 7 shows the impact from phase errors of 10% and 20% of the wavelength spread across 11 symbols (first through last TRS symbol in a sub-frame). There is less than 0.6 dB signal loss of the main correlation peak associated with the 20% phase error option, so the overall SNR impact is small. The phase error mainly manifests itself as alias terms in the correlation function. These spurs are spaced at 1/6th of the symbol duration, or ~ 3331 km, which is less than the maximum ionospheric delay of ~ 2000 km. For the 20% phase error case, the strongest alias term is more than 12 dB weaker than the main correlation peak, so it should be detected and rejected easily.

A 20% phase error for a 100 kHz center frequency corresponds to approximately 600 m. Incurring such a phase error across 11/12th of a second corresponds to a speed of 655 m/s (nearly Mach 2). Thus, a receiver with an accurate clock would be quite robust against motion impact, even without tracking the received frequency.

Instead looking at impact from clock inaccuracies, the Doppler equation produces a Δf value of ~0.22 Hz for a speed of 655 m/s and a center frequency of 100 kHz. The frequency offset corresponds to ~ 1.45%

of the proposed 15 Hz sub-carrier spacing. Such an offset would have a small impact on orthogonality with neighboring stations. Finally, a 0.22 Hz clock error at 100 kHz corresponds to 0.22 /1e5 = 2.2 e-6 or 2.2 ppm. This means that a stationary user could use an XO with a moderate accuracy of 2.2 ppm without needing a frequency tracking loop. Splitting the difference between motion and clock accuracy, a user with a ~ 1 ppm quality XO could support speeds of ~ Mach 1 without the need for a frequency tracking loop.

Conclusion

In this paper we have proposed a design for a 100 kHz broadcast system, LORAN-5G, in support of the National Timing Security and Resilience Act. The physical layer proposal calls for use of OFDM and it has background in lessons learned from 5G-NR signal design for positioning. While 5G-NR uses radically different frequency bands for operation, a 100 kHz broadcast system shares fundamental design considerations and it can be modelled as a terrestrial cellular network (albeit one with only downlink). The Timing Reference Signal (TRS) has been designed with inherent orthogonality that alleviates near-far issues. Furthermore, the TRS is robust against low-ionospheric multipath, and it supports operation at very high speed yet requiring user equipment with only moderate XO quality. Finally, LORAN-5G supports an in-band data channel with a > 2.6 kb raw data rate per station. The data channel can be used to broadcast large-scale absolute time information, station location, clock corrections and differential corrections to support a fully stand-alone operation for users needing resilient timing service and/or positioning service.

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