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Beacon Signaling for Expedited Cell Search Procedures in NTN NB-IoT

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ABSTRACT

Three cellular standards have been considered for Non-Terrestrial Networks (NTN): NB-IoT, eMTC and NR, each having had features introduced to accommodate the challenges of the NTN case. In Terrestrial Networks (TNs), it is reasonable to expect continuous coverage when a UE is stationary within reach of a base-station (eNB) with rare exceptions of downtime due to failures or catastrophic events. The same continuity cannot be assumed in NTN for sparse eNB constellations or during the rollout of dense eNB constellations. Therefore, a feature of the NTN IoT protocols - NTN NB-IoT & NTN eMTC - is the support of discontinuous RAN coverage.

Cell search is a core task of NTN UEs serviced by non-geostationary (NGSO) constellations. Initially, when UEs are booted up, unless a recent ephemeris has been provisioned to it, the UE must first discover a valid eNB by employing repeated cell searching. UEs will have to keep doing cell search each time they wish to access a cell again after losing or dropping connectivity. Intermittent coverage gaps, which occur in dense constellations due to system failures, during rollout or inherently in sparse constellations, exaggerate the number of cell search attempts required by a UE before finding an appropriate cell to camp on. These latter cases of intermittent coverage can be mitigated by the coverage prediction features for discontinuous coverage.

In this paper, a beacon signal, which can be transmitted within the white-spaces of stand-alone NB-IoT, is introduced. The beacon signal is designed to expedite the cell search procedure in NTN NB-IoT in NGSO constellations by: (1) Allowing for easy and early detection of the presence of a cell, (2) encoding preliminary information for the UE to assess whether to continue cell search at that early point and (3) providing helpful information to the synchronisation procedure. The performance of the beacon signal is simulated and evaluations show a fair improvement over utilizing legacy synchronization signals for cell detection both in terms of speed and SNR.

INTRODUCTION

Use-cases such as logistics, agriculture 4.0 and environmental monitoring require wide and ubiquitous wireless coverage to provide connectivity to sensors and actuators within the Internet of Things (IoT) paradigm. In some use-cases long battery lifetimes, up to and beyond ten years, is also a necessity due to the cost of accessing and replacing or recharging deployed devices.

Low Power Wide Area Networks (LPWANs) have surged to address the needs of logistics, agriculture 4.0 and environmental monitoring use-cases. One of the multiple competing LPWAN technologies is NB-IoT, which is a cellular technology operating within licensed spectrum with a central coordinating node within the Radio Access Network (RAN) which is referred to as the (evolved) Base-station Node (eNB). These architectural choices of coordinated synchronous communication allow NB-IoT to perform in a more reliable manner with higher Quality of Service (QoS) than other LPWANs.

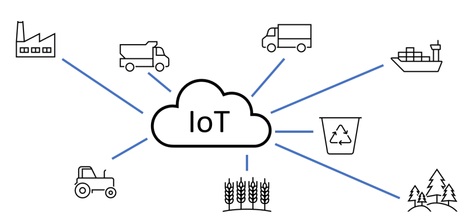

Figure 1: Use-cases for LPWANs in the Internet of Things paradigm.

The price of NB-IoT modems is not far off the price of LoRa modems even with the comparatively increased complexity of the NB-IoT waveform. For example off the shelves LoRa modems can be bought for around 11$ and NB-IoT+eMTC modems for around 22$ with GPS onboard. This can be attributed to the design of NB-IoT being based on the LTE waveform and effectively re-utilizing several components allowing for efficient economies of scale.

This same idea of reusing waveform components to achieve great cost reductions through economies of scale has seen the 3rd Generation Partnership Project (3GPP) take aim at standardizing cellular Non-Terrestrial Networks (NTN) based on NB-IoT, eMTC and NR. Under the 5G umbrella, the cellular networks targeting service of massive Machine Type Communications (mMTC) are NB-IoT and eMTC. In the context of NTN, NB-IoT and eMTC are commonly referred to together as IoT NTN, but may be referred to individually as NTN NB-IoT and NTN eMTC. NTN IoT takes LPWANs to the next level by bringing truly ubiquitous coverage globally for logistical and environmental applications.

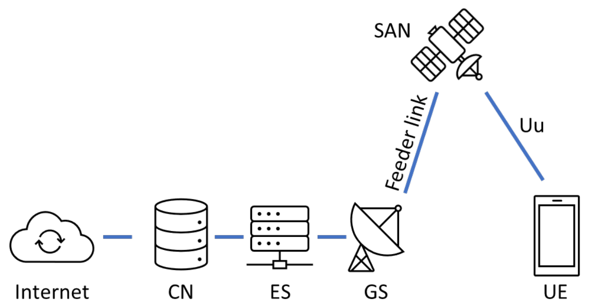

Figure 2: Satellite network architecture consisting of User Equipment (UE), SAN, Ground-Station (GS), Edge-Server (ES) and Core Network (CN).

In the standardization regime 3GPP studied NTN in Release 16 with Release 17 being the first specification of IoT NTN and NR NTN. Release 17 features for NTN IoT include (1) architectural support for Satellite Access Nodes (SANs) both for LEO and GEO and (2) energy-saving features for discontinuous coverage in constellations that can not provide full continuous spatial-temporal coverage of the globe, which is expected to be a key enabler during the roll-out of constellations. The standardized architecture refers to the placement of the eNB at the ES, see Fig. 2. Notably, to the knowledge of the authors, there is nothing hindering placement of the eNB within the SAN according to Release 17.

In Release 18 new features to enhance the service in particular of longer communication sessions are being defined, namely (a) GNSS validity duration negotiation between UE and eNB and (b) disabling of HARQ retransmissions. Release 19 is expected to introduce new service cases that require a regenerative architecture, for example, 'Store and Forward' and satellite loop-back (LAN via satellite).[1]

In 3GPP's NTN study three of the key issues identified were (1) closing the link-budget for satellites and handheld UEs and (2) the effect of Doppler in LEO-SAN networks[2,3] and (3) mobility within LEO-SAN networks. In a LEO constellation the SAN mobility will result in a need for detecting the SAN cells in an efficient manner, which is accentuated by both the Doppler and link-budget conditions. The maximum absolute Doppler is 24 PPM and the maximum Doppler rate is 0.27 ppm/s for a LEO-600 orbit.[4] This translates to 24 kHz and 270 Hz/s for a 1 GHz carrier, which can be scaled to any carrier frequency. The link budget for a small satellite was investigated in our SSC21 paper[5] and found to be near 0 dB or several dBs below for many elevation angles.

NB-IoT was designed to fit in-band of LTE and so NPSS, NSSS and NPBCH contain a white-space for the first 3 OFDM symbols as indicated in Fig. 3. These white-spaces are unused in stand-alone NB-IoT and could instead be used to introduce a beacon signal to aid with fast cell detection. In this paper, we design a simple beacon waveform and simulate receiver performance.

BEACON DESIGN

The beacon signal, S_{beacon}, which will be inserted in the white-spaces mentioned above, should be designed to be detectable at a low SNR and with a large Doppler shift. We adopt a simple sinusoidal waveform as per (1): an exponential in the I/Q domain, which maximises the power output of the amplifier and allows for both amplitude, frequency or phase detection.

$$S_{beacon}[k] = \exp\left(i \cdot 2\pi \cdot k \cdot \frac{f_{beacon}}{f_s}\right) \tag{1}$$

where f_s is the sampling frequency, k is the sample index and f_{beacon} is the beacon frequency.

The beacon signal in the IQ-domain is depicted in Fig. 4. Notice how the amplitude, or transmitted power, of the beacon signal remains constant and the phase of the signal changes over time. The rate at which the phase changes is given by the angular beacon frequency $2\pi \cdot f_{beacon}$.

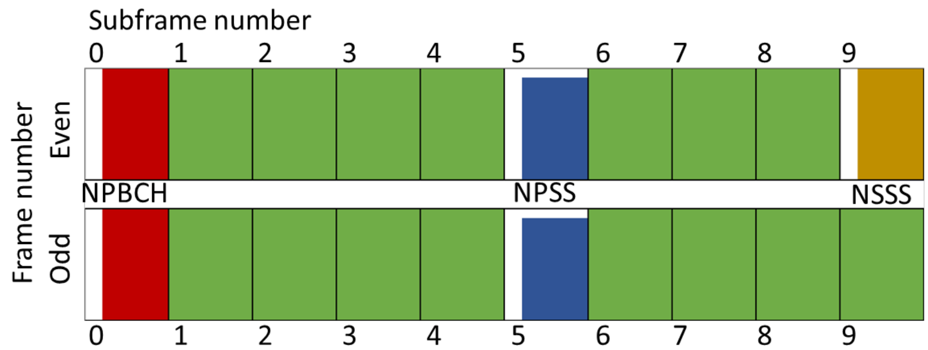

Figure 3: White-spaces within stand-alone NB-IoT odd and even frames.

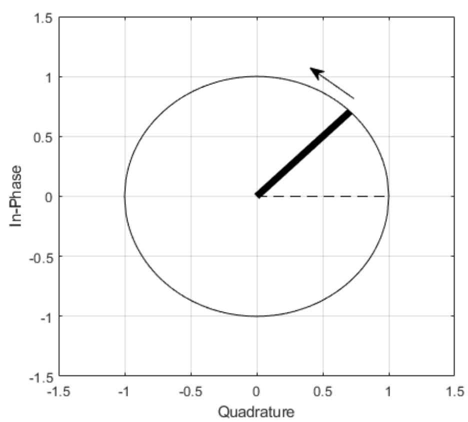

Figure 4: In-phase and Quadrature diagram of beacon signal.

The primary function of the beacon is the fast detection of SANs in challenging link-budget conditions, but as a secondary feature the beacon signal may relay access information. The PLMNID of the SAN cell, for example, could allow UEs to evaluate whether to continue with the more costly regular synchronization process of NTN NB-IoT, look for another cell or enter a sleep mode to attempt a cell search at a later time.

In this paper, the beacon signal and beacon detector consist of two stages as depicted in Fig. 5: A preamble stage for detection and a demodulation stage to decode some access information as described above.

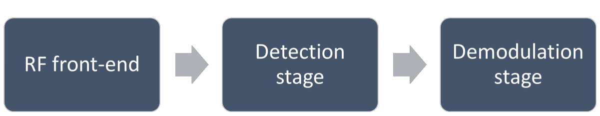

Figure 5: Two-stage beacon signal detector

Detection Stage

Individual beacon signals can as be detected by means of signal amplitude (energy), frequency or phase detection. Individual detections can be seen as representing a time-series and the full beacon detector can utilize the periodicity of these detections to look for an auto-correlation that fit with the white-space pattern, e.g. 5 ms periodicity.

Each individual beacon signal shall start at the same phase so that at least up to 8 repetitions of the signal can be constructively combined with less than a single sample drift as indicated by Table 1.

Table 1: Sampling drift over combinations.

f_c	Reps	Doppler [kHz, Hz/s]	Drift [Hz]	Drift [ns]
1 GHz	8	24, 270	10.8	432
2 GHz	8	48, 540	21.6	432
4 GHz	8	96, 1080	43.2	432

Demodulation Stage

Information can be modulated onto the beacon in several ways, by means of absolute or differential phase, frequency, amplitude, or timing of the individual beacon signals.

In this paper, we shall focus on FSK where we will not use the outer ±45 kHz to allow a UE to search around candidate ARFCNs while inherently taking into account potential Doppler. This leaves 90 kHz for FSK, which can be divided into a number of a-priori agreed bins frequency bins, which allows for encoding for the number of bits as given in Table 2. Spare states can be used as preambles and/or postambles to indicate the beginning or end of information. The number of bits required to encode a PLMNID is 24 bits.

Table 2: Sampling configurations.

Config	Sampling rate	FFT size	Bin size	Bits per symbol
A	1920 kHz	512	3.75 kHz	4.58 bits
B	960 kHz	256	7.5 kHz	3.58 bits
C	480 kHz	128	15 kHz	2.58 bits
D	240 kHz	64	30 kHz	1.58 bits

BEACON RECEIVER

The beacon receiver works in two stages as per the designed beacon functionality; First the presence of a beacon is detected, then a PLMNID is demodulated from the beacon signal.

Detection Stage

In this subsection, a simple detector design, which is fully implementable in hardware circuitry or VHDL is presented.

The detector may sample the NB-IoT waveform at a decimated rate. The samples are logged for future attempts at maximal ratio combining. The detector uses sample windows of a size greater than the number of samples expected in a beacon, at regular intervals which we shall fix at one half of the window length. The window is then combined with n_{Rep} prior windows that are the expected beacon interval of 5ms apart. The combined window is fed to an FFT, which will find if there is a high degree of activity on any frequency bin. The results for all frequency bins with an FFT output larger than a threshold (dependent on the FFT size) are logged over time. This creates a time-series of likely detections of the individual beacon signals. This time-series autocorrelated and the peak of this autocorrelation (outside of n=0) must be at the sample corresponding to 5ms±1 sample.

Demodulation Stage

After the detection of a beacon, the detector may simply revisit the logged FFT results to find the frequency bin of subsequent repeated individual beacon signals.

The resulting sequence of beacon symbols can be directly mapped from FSK to the PLMNID where the first symbol is used as a preamble. The required beacon period to observe the PLMNID is given by (2) where m is the number of bits per symbol.

$$T_{beacon} = (1 + \frac{24}{m}) \cdot n_{Reps} \cdot 5[ms] \quad (2)$$

PERFORMANCE RESULTS

The performance of the designed beacon signal and receiver was simulated in Matlab©[6] using an NB-IoT signal as a baseline and adding the designed beacon to the signal along with varying levels of noise resulting in the received signals depicted in Fig. 6. The various detector algorithms from FFT to auto-correlation and demodulation were run in an online manner on a sampled and decimated version of this incoming signal.

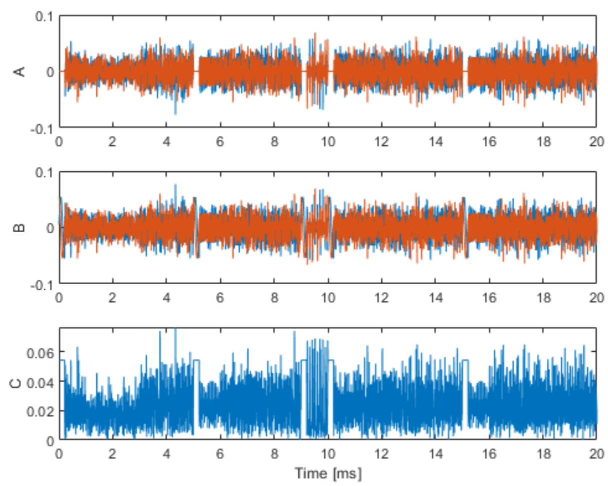

Figure 6: A) I/Q time-series of stand-alone NB-IoT waveform. B) I/Q time-series of NB-IoT with added beacon signalling. C) Power profile in NB-IoT waveform with added beacon signalling

Detection Stage

The detection success probability were simulated in 5 dB steps for SNR levels from -35 to -5 dB. The results can be found in Fig. 7 and Table 3. The false detection probability is virtually zero as it is minimized first due to the combining of beacon repetitions for the detection of individual beacons and secondly by the requirement of correlated timing between consecutive detections of individual beacons.

Table 3: Detection probabilities

SNR	Detection rate	Sampling rate	FFT size
-10	∼100%	240 kHz	64
-10	∼100%	480 kHz	128
-15	>80%	480 kHz	128
-20	∼100%	1.92 MHz	512

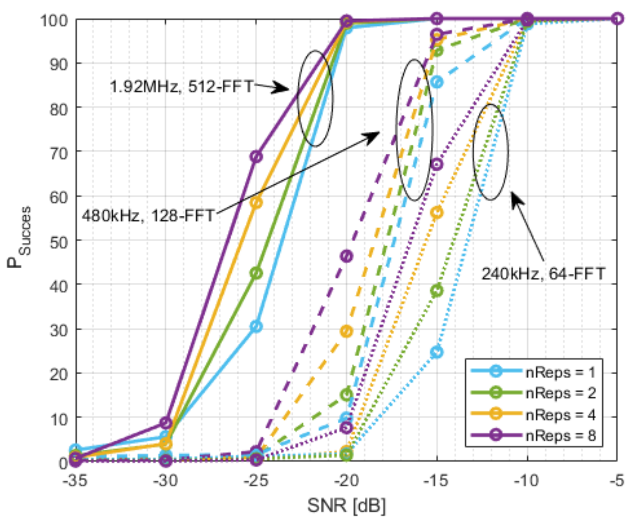

Figure 7: Detection probabilities for the configurations A, C and D.

Demodulation Stage

A period of 280ms, 360ms, 520ms and 1000ms for configurations A, B, C and D, respectively, must be observed for 8 repetitions, however at just two repetitions the period is merely 35ms, 45ms, 65ms and 125ms, respectively.

CONCLUSION

The designed beacon outperforms the performance of conventional NPSS and NSSS detection techniques, which in our SSC21 paper[5] were found to be >4 sec below -10 dB SNR. The performance increase is large enough that heavy decimation may be used in the front-end to limit computational load and access information can be modulated onto the beacon while still maintaining an improvement in the SNR.

This presents a small gain in energy efficiency during each attempt at cell search, which is further increased by the possibility of modulating access information, e.g. the PLMNID on the beacon signal. When scaling this increased energy efficiency of cell search by the large number of cell searches that are expected in the case of NGSO (cell-moving) NTN then this proposed solution really shows its worth.

ACKNOWLEDGEMENTS

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