Dto. de Ingeniería Eléctrica y de Computadoras
Universidad Nacional del Sur

DIEC

An introduction to cellular IoT: Signal processing aspects of NB-IoT

Juan Cousseau (jcousseau@uns.edu.ar)
Laboratorio de Procesamiento de Señales y Comunicaciones
Instituto de Investigaciones en Ingeniería Eléctrica - CONICET

NEON

Co-funded by the Erasmus+ Programme of the European Union

Outline

Outline…

NB-IoT layers

NB-IoT layer functions: PDCP, RLC, MAC
Congestion control : ACB and EAB
Power efficiency: PSM, I-DRX, C-DX

NB-IoT Idle and Connected Mode Procedures

Idle Mode
Connected Mode

NB-IoT DL synchronization methods

System model
Cell search
Timing and frequency acquisition

NB-IoT UL synchronization

NPRACH preamble design
NPRACH estimation methods 1 and 2

NB-IoT in ISM bands

Characteristics - Alternatives for NB-IoT

NB-IoT in ISM bands

Bands used for civil communication systems can either be licensed or unlicensed.

Licensed bands are bands that require a license for operation. A license usually entails the sole right of operation in a specific band and is made available by a government agency through auctioning.

With a licensed band an operator can thus have full control over the interference within the band, enabling very efficient multiple access and coordination schemes.

The auction price per useful MHz in the U.S. have been on the order of hundreds of millions of dollars in the last decades.

DIEC

NB-IoT in ISM bands

Unlicensed bands on the other hand are open for anyone to use, as long as one follows whatever rules are imposed on these bands (e.g. by using certified equipment).

These rules specify how coexistence is achieved by the use of multiple access methods (power limitations, duty cycles, spectrum spreading or back off in contention schemes) that will prevent each user from operating in the most efficient manner, even when they are alone.

And when they are not alone, the interference might be unpredictable and too strong for reliable operation.

Advantages of unlicensed bands: affordable operation (ex. Wi-Fi); the spectrum may be used more efficiently (license holders typically do not use their bands at all times or at all geographical places).

DIEC

NB-IoT in ISM bands:
Regulations

Different emission regulations will apply for different types of devices. FCC, for example, classify radiators in: intentional (wireless communication devices), unintentional and incidental.

Rules for communication type of devices typically include:

- What the specific operating frequencies are.
- How much power a device can emit.
- How much spectral leakage or what modulation methods that are allowed.
- How much spurious emissions from harmonics that are allowed.
- Specific interference mitigation schemes, such as duty cycles or spectrum spreading.

The most important regulation is power emission limit : ERP (equivalent radiated power) or EIRP (equivalent isotropically radiated power). EIRP = ERP + 2.15 dB

DIEC

NB-IoT in ISM bands:
Regulations for US ISM bands

FCC use the term ISM (Industrial, Scientific and Medical) bands for ultra high frequency bands that allow unlicensed operation by low power devices.

While there are many different ISM bands to choose from, we will narrow down our choices as follows. First of all, high carrier frequencies have two important disadvantages. They tend to have poor propagation properties and they require power hungry and expensive active components.

Since NB-IoT is already struggling to increase its coverage and reduce the device cost and power consumption, we will limit our considerations. We draw the line at 1 GHz (902–928 MHz). The 2.4 GHZ due to the popularity introduces high interference.

DIEC

NB-IoT in ISM bands:
Regulations for US ISM bands…

Considering the 915 MHz band, by limiting the emissions to EIRP = -1.23 dBm, the band can be used freely with no further major restrictions.

This power is not enough to create a functional cellular system. By following a FHSS scheme, much higher output powers are allowed.

The maximum possible power of EIRP = 36 dBm is allowed if:

- The 20 dB bandwidth is less than 200kHz.
- FHSS is used and
  - At least 50 channels are used for hopping.
  - These channels have non overlapping 20 dB bandwidths.
  - At most 0.4 s dwell time per channel per 20 s period is used.
  - The hopping follows a pseudo-random pattern.
- The antenna gain is at least 6 dBi.

DIEC

NB-IoT in ISM bands:
Regulations for US ISM bands…

Since the each hopping pattern must be pseudo-random, it has to be different between nearby eNB for them to be considered separate systems.

The UE will not know the exact hopping pattern until is has decoded the cell ID, which happens in the end of the synchronization process when the NSSS is detected. At this point, the timing is known up to a multiple of 80 ms.

A feasible way to synchronize the UE to the eNB channel hopping is to use a channel dwell time that is a multiple of 80 ms.

The UE can then listen to one channel until the NPSS and NSSS is detected and then do hypothesis testing of the number of 80 ms periods until the next hop by sampling both the current and the next channel.

NB-IoT in ISM bands:
Regulations for US ISM bands…

Furthermore, by having the MIB transmission interval of 640 ms being a multiple of the channel dwell time, the MIB boundary is given by knowing the hopping boundary, the hopping pattern and the index of the current channel. This simplifies MIB detection.

The largest channel dwell time satisfying the previous criterion and the 0.4 s limit is 320 ms.

The conclusion here is that NB-IoT-U should be able to finish both NPSS and NSSS processing within 320 ms.

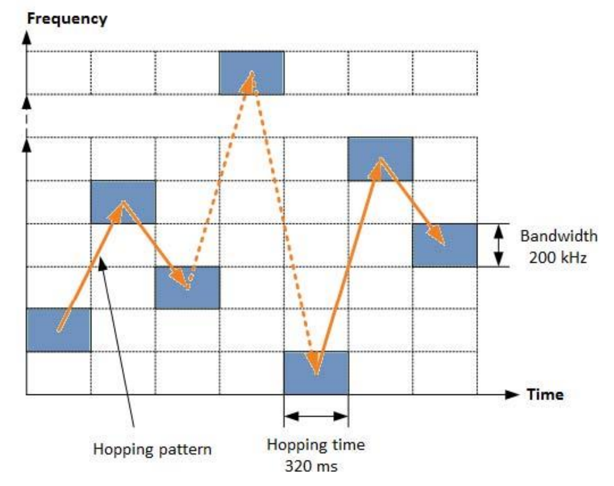

Figure 4.1: Pseudo-random hopping pattern.

NB-IoT in ISM bands:
EU Short Range Devices

In the European Union, low power radiating devices are called Short Range Devices (SRD). These correspond to ISM in the U.S. and include NB-IoT devices.

The 869.4 (to 869.65) MHz band is by far the best candidate in terms of power, which is a crucial factor for NB-IoT coverage: ERP is 27 dBm (EIRP of 29.15 dBm).

By concatenating many channels, this band can also be operated in a mode that utilizes the full bandwidth of 200 kHz, which matches the 915 MHz ISM band nicely and allows for a similar implementation.

The 10% duty cycle means that: A device can transmit for a maximum total time of 360 s per hour; each transmission can have a maximum length of 36 s; a minimum off time of 3.6 s is required between transmissions.

NB-IoT in ISM bands
Alternatives for NB-IoT-U

Temporal diversity (coherent combining)

- NPSS densification
- NPSS enhancement

Spatial diversity

- Artificial fast fading

NB-IoT in ISM bands
Time diversity: coherent combining

With *N* transmissions of signal *s* with AWGN *n*, the resulting SNR would be

$$\mathrm{SNR}_{new} = \frac{E\{|Ns|^2\}}{E\{N|n|^2\}} = N \times \mathrm{SNR}_{old}$$

and the SNR gain would thus be 10 log10 *N* dB. This in an example of time diversity.

DIEC

NB-IoT in ISM bands
Time diversity method 1: NPSS densification

Due to the time window for synchronization the idea is to increase signal energy by adding one extra NPSS subframe.

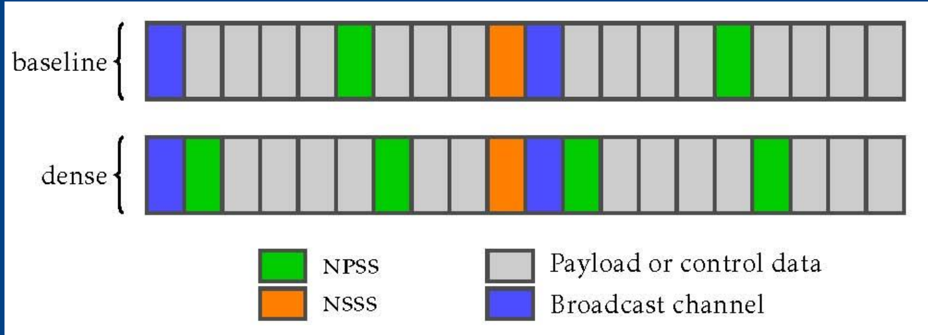

Figure 5.1: *New dense frame structure with an extra NPSS subframe.*

One or a few of the hopping channels can be used.

NB-IoT in ISM bands
Time diversity method 1: NPSS enhancement

Since now NB-IoT will be stand-alone, it is possible to use the LTE reserved symbols.

This means that the first 3 symbols in every subframe are available. They could be used to extend the NPSS by modifying or replacing it.

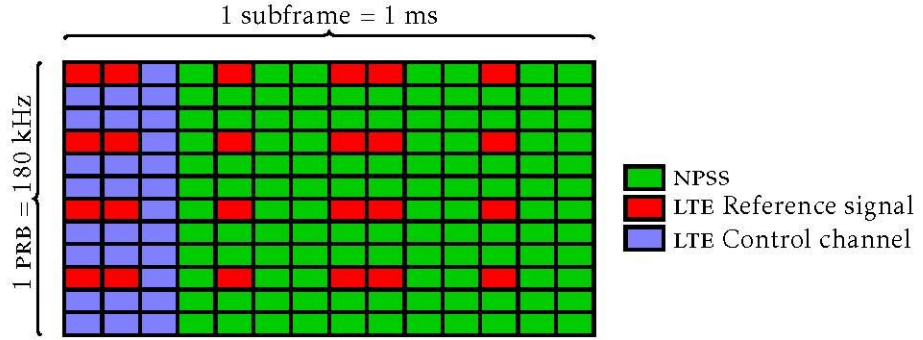

Figure 3.4: NPSS resource mapping, inband deployment. Each row represents one subcarrier.

NB-IoT in ISM bands
Spatial diversity

Many different channel models incorporate the fading propagation phenomenon, which is the change in reception quality brought on by time-varying channels.

One important type: multipath fading.

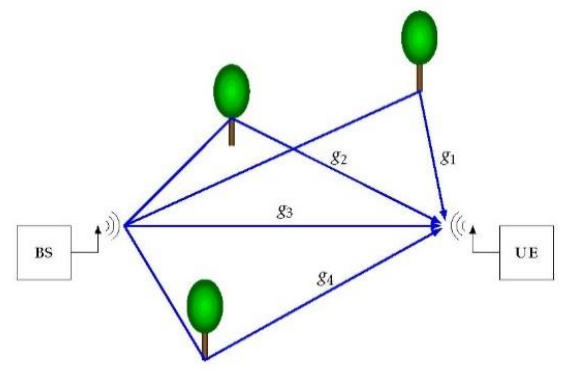

Figure 6.1: *Single-antenna multipath propagation*

This is where diversity comes in. By having several Transmit antennas, we can utilize the fact that not all of them will be at a deep fade at any give time…

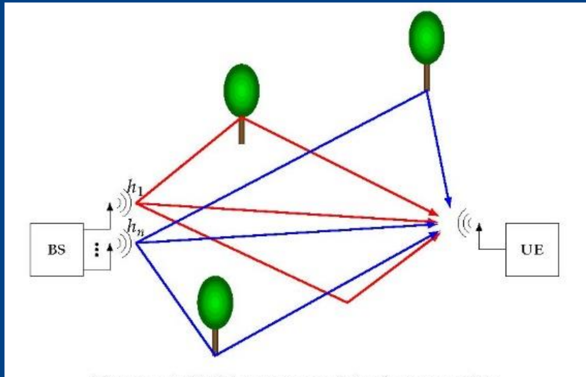

Figure 6.2: *Multi-antenna multipath propagation*

NB-IoT in ISM bands
Spatial diversity

What can be done, without CSI at the transmitter, is to average out the SNR over time and space by blindly altering the channel.

By regularly changing the filtering at each antenna, a faster fading will be experienced at each UE.

This could increase the chance that each UE has at least some period of good reception during the 320 ms synchronization period.

We call this technique artificial fast fading.

DIEC

Conclusions

- A basic characterization of licensed and unlicensed bands is made to put in evidence how NB-IoT can be used in the latter case.
- Since unlicensed band introduce power and time constraints, frequency hopping is the solution to be considered.
- To overcome the time limitation of frequency hopping, different alternatives could be considered: NPSS densification, NPSS enhancement and spatial codes for artificial fast fading.

Some references

Books

M.O. Pun, M. Morelli and C.C-J. Kuo, “Multicarrier techniques for wireless communications: A signal processing perspective”, Imperial College Press, 2007.

O. Liberg, M. Sundberg, Y.-P. E. Wang, J. Bergman, J. Sachs, “Cellular Internet of Things Technologies, Standards, and Performance”, Academic Press 2018.

H. Fattah, “5G LTE Narrowband Internet of Things (NB-IoT)”, CRC Press 2019.

Articles

M. Morelli, C.-C. Jay Kuo and M.-O. Pun, “Synchronization Techniques for Orthogonal Frequency Division Multiple Access (OFDMA): A Tutorial Review”, Proceedings of the IEEE, Vol. 95, No. 7, July 2007.

A. Ali and and W. Hamouda, “On the Cell Search and Initial Synchronization for NB-IoT LTE Systems”, IEEE Communications Letters, Vol. 21, No. 8, Aug. 2017.

J-K. Hwang, C-F. Li and C. Ma, “Efficient Detection and Synchronization of Superimposed NB-IoT NPRACH Preambles”, IEEE Internet of Things Journal, Vol. 6, No. 1, Feb. 2019.

X. Lin, A. Adhikary and Y.-P.E. Wang, “Random Access Preamble Design and Detection for 3GPP Narrowband IoT Systems”, IEEE Wireless Communications Letters, Vol. 5, No. 6, Dec. 2016.