# Implementing NB-IoT in Software - Experiences Using the srsLTE Library

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***Abstract*—NB-IoT is the 3GPP standard for machine-to-machine communications, recently finalized within LTE release 13. This article gives a brief overview about this new LTE-based radio access technology and presents a implementation developed using the srsLTE software radio suite. We also carry out a performance study in which we compare a theoretical analysis with experimental results obtained in our testbed. Furthermore, we provide some interesting details and share our experience in exploring one of the worldwide first commercial NB-IoT deployments.**

***Keywords*—NB-IoT, LTE, Software Defined Radio, srsLTE**

## I. Introduction

Narrowband Internet of Things (NB-IoT) has been standardized by 3GPP in Release 13 as a new air interface with the aim to make LTE suitable for low-cost massive machine-type communication (m-MTC). NB-IoT is heavily based on LTE but makes a number simplifications and optimizations in order to reduce device costs, minimize power consumption and to make it work in unfavourable radio conditions.

This work presents an implementation of the NB-IoT standard, developed using the srsLTE software radio suite within the FP7 FLEX-IoT project. Since 2008, the Future Internet Research and Experimentation (FIRE) initiative has bridged the gap between visionary research and large-scale experimentation on new networking and service architectures and paradigms. The FLEX (FIRE LTE testbeds for open EXperimentation) project provides an open and operational LTE experimental facility based on a combination of configurable commercial equipment, configurable core network software, open-source components, and sophisticated emulation and mobility functionalities. Under the FLEX-IoT project, we have integrated our high performance software radio UE (srsUE) as an extension to the FLEX testbed facilities and extended the FLEX testbed facilities to include the NB-IoT features of 3GPP LTE release 13 for LPWAN. For an excellent overview about NB-IoT in general and it's differences to LTE in particular the interested reader is referred to [1] and [2].

In this report we provide a brief overview about NB-IoT and describe the available channels and signals in Section II. We then discuss the architecture of srsLTE and how the new NB-Iot components have been integrated into it. The main contributions of this article is a performance analysis carried out in Section IV. We study the achievable throughput in the downlink and compare results obtained from practical experiments with those from a theoretical analysis. In Section V we share our experience in exploring one of the first commercial NB-IoT deployments. Finally, we conclude the paper in Section VI.

## II. NB-IoT Overview

This section provides a brief overview about NB-IoT, it's transmission schemes, downlink (DL) and uplink (UL) channels and signals and the different deployment schemes.

### A. Transmission schemes, time structure and deployment options

NB-IoT uses the same downlink transmission scheme like normal LTE with OFDMA with a subcarrier spacing of 15 kHz. 12 subcarriers are combined to form a single carrier with a bandwidth of 180 kHz, i.e., NB-IoT only uses one physical resource block (PRB) instead of up to 100 PRBs. In the time domain, it also uses the same frame structure with frames of 10 ms length. Each frame consists of 10 subframes of 1 ms length and each subframe consists of 2 slots with a length of 7 OFDM symbols each. NB-IoT only defines the normal cyclic prefix. In addition to that, NB-IoT also defines the concept of so-called hyper frames. Similar to the system frame number (SFN), the hyper frame number (HFN) is also a ten-bit wide number that is incremented whenever the SFN wraps around, i.e., every 10240 ms.

In the uplink, NB-IoT provides two options: single and multi-tone transmissions. In the latter case, which is the default option, it uses the same SC-FDMA scheme with a 15 kHz subcarrier spacing and a total bandwidth of 180 kHz as LTE.

NB-IoT offers multiple deployment options. It can be deployed in standalone mode, i.e., without any pre-existing LTE network, or together with an already deployed LTE network. The latter has the advantage that existing sites can be used to roll out an IoT network without heavy investments in new hardware. In this case, the NB-IoT carrier can be placed inside one of the subcarriers of an existing LTE cell or in the guardbands of a cell. In Release 13, 3GPP has also standardized a new UE device category for NB-IoT, called Cat-NB1.

### B. Downlink

Release 13 of the 3GPP standard defines six physical DL channels/signals for NB-IoT, all of which will be briefly described below [3]. Because NB-IoT only uses a single PRB, the channels are only multiplexed in time-domain. Figure 1 depicts how all DL signals are transmitted over the length of two frames.

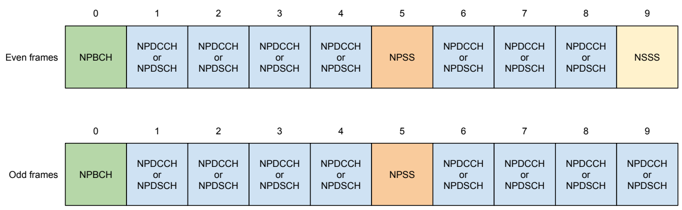



Fig. 1: NB-IoT downlink frame structure and time multiplexing (reproduced from [1]).

*1) Narrowband Primary Synchronization Signal (NPSS):* The NPSS, as well as the NSSS described below, are primarily used for initial cell search and for acquiring time and frequency synchronization. The NPSS is transmitted in every frame in subframe number 5. It only uses 11 of the 14 available OFDM symbols of the subframe to protect a potential LTE transmission in the same subframe. The signal itself consists of a single length-11 Zadoff-Chu (ZC) sequence that is either directly mapped to the 11 lowest subcarriers (the 12th subcarrier is empty in the NPSS) or is inverted before the mapping process. After successful detection of the NPSS, a NB-IoT UE is able to determine the frame boundaries of a DL transmission.

*2) Narrowband Secondary Synchronization Signal (NSSS):* The NSSS is transmitted every 20 ms in every even-numbered frame in subframe number 9. The signal consists of a length-132 sequence that is generated from a scrambling sequence and a length-132 ZC sequence. The NSSS only carries the cell ID.

*3) Narrowband Reference Signal (NRS):* The NRS is required by the UE to successfully demodulate any of the data or control channels. For this purpose, the eNB broadcasts a known pilot signal that can be used to estimate the DL channel. With this knows reference, the UE tries to correct the effects of the channel before demodulating the signal. The NRS is transmitted in every subframe carrying either the NBPCH, NPDCCH or the NPDSCH. It is distributed over 4 OFDM symbols (the last and second last symbol of each slot) and uses a total of 8 resource elements (RE) per antenna port.

*4) Narrowband Physical Broadcast Channel (NPBCH):* The NPBCH is the first physical channel that a UE attempts to receive and demodulate after synchronizing with a cell. The NPBCH conveys important information that is encoded in the Narrowband master information block (MIB-NB), such as the SFN (the four most significant bits), the HFN (the two least significant bits), system information block (SIB) scheduling information and the NB-IoT operation mode. In order to allow successful decoding of the MIB-NB also in extraneous radio conditions, it is transmitted in the first subframe of every ever frame over a total period of 640ms, i.e., over 64 frames. For this purpose, the MIB-NB signal is split into 8 blocks, each of which is repeated 8 times. The NPBCH is QPSK modulated and uses a tail-biting convolution encoding (TBCC).

*5) Narrowband Physical Downlink Control Channel (NPDCCH):* The NPDCCH is the only control channel defined for NB-IoT, i.e., there is now uplink counterpart like in normal LTE. It carries the DL and UL scheduling grants, acknowledgment information for UL transmissions, paging indication, system information update and random access response (RAR) scheduling information. For NB-IoT only three DL control information (DCI) formats are specified and only three possible positions exist in the NPDCCH. This simplifies the decoding overhead for the UE significantly compared to LTE. Like the NPBCH, the NPDCCH is also QPSK modulated and protected using TBCC.

*6) Narrowband Physical Downlink Shared Channel (NPDSCH):* The NPDSCH is the main data channel and carries SIBs, upper layer data, and random access response (RAR) messages.

### C. Uplink

The 3GPP set of specifications defines two uplink channels, the Narrowband Physical Random Access Channel (NPRACH) and the Narrowband Physical Uplink Shared Channel (NPUSCH). It is interesting to note that there is no equivalent to the Physical Uplink Control Channel (PUCCH) of LTE in NB-IoT. In addition to that, NB-IoT defines the Narrowband demodulation reference signal (DMRS).

*1) Narrowband Physical Random Access Channel (NPRACH):* As in normal LTE, the NPRACH is used by an UE to signal the eNB that it wants to establish a connection with it. The attachment procedure is a contention-based access method in which the UE transmits a random access preamble. One such preamble consists of four symbol groups each of which is transmitted on a different subcarrier. Each symbol group in turn consists of the cyclic prefix (CP) plus 5 symbols, with a total length of either 1.4 ms or 1.6 ms, depending on the format defined by the eNB. In order to increase the coverage the eNB may request a UE to repeat the preamble transmission up to 128 times. The subcarriers used to transmit the NPRACH follow a certain hopping pattern that depends on a randomly selected initialization value.

*2) Narrowband Physical Uplink Shared Channel (NPUSCH):* The only means to communicate data from the UE to the eNB, except for the random access, is over the NPUSCH. There exist two formats, NPUSCH format 1 is used to carry user data, whereas format 2 is used to carry uplink control information. Upon reception of the preamble, the eNB responds with the random access response (RAR) which initiates the transmission of the first scheduled transmission by the UE (Msg3). After the contention resolution sent from the eNB, the NB-IoT random access procedure is complete.

*3) Narrowband demodulation reference signal (DMRS):* In order for the eNB to be able to estimate the UL channel, the UE transmits a demodulation reference signal (DMRS) that is multiplexed with the actual NPUSCH symbols. Depending on the NPUSCH format, i.e. either format 1 or format 2, one or three symbols per SC-FDMA slot are used to transmit the DMRS. For example, for the case of format 1 NPUSCH with a subcarrier spacing of 15 kHz, the 4th symbol of every slots contains the DMRS symbols in all allocated subcarriers.

*4) Uplink Baseband Signal Generation:* In order to generate the SC-FDMA baseband signal for the NB-IoT UL it is important to note an interesting difference to normal LTE. In fact, each modulation symbol (both data and reference symbols) for all UL transmissions undergo a phase rotation that depends on the position of the particular symbol. This reduces

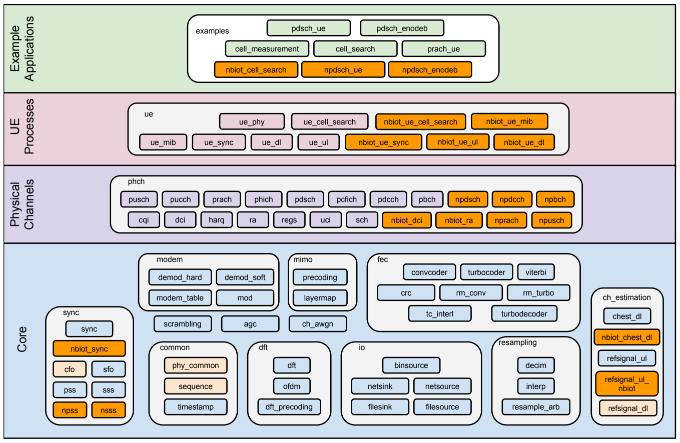



Fig. 2: srsLTE's modular architecture with new NB-IoT components.

the peak-to-average power ratio (PAPR) because it effectively yields a $\pi/2$-BPSK or $\pi/4$-QPSK modulation scheme with phase continuity between symbols, i.e., no zero-crossing in the constellation diagram between symbols.

## III. srsLTE

srsLTE is a high-performance open-source software radio LTE physical layer library [4]. It is specifically designed to support new air interface modifications and enhancements using a modular architecture with clean inter-component interfaces.

### A. Library Structure

Figure 2 shows the modular architecture of the srsLTE PHY-layer library. Functional modules are organized into a hierarchy from elementary DSP components at the bottom to physical channels, processes and example applications at the top.

### B. NB-IoT Extension

As part of the FLEX-IoT project, srsLTE has been extended to support the new NB-IoT radio access technology. In doing so, we leveraged from the great modularity and extensibility of the library and consequently followed the same approach for the NB-IoT physical layer components, including all DL/UL channels and signals defined in the standard. All orange blocks in Figure 2 have been added to srsLTE during the course of the NB-IoT extension.

srsLTE provides two example applications that act as PHY-only NB-IoT eNodeB and UE, similar to the already existing counterparts for LTE. The `npdsch_enodeb` example acts as an eNodeB by accepting data traffic on a TCP socket and transmitting it using the NB-IoT downlink physical channels. The number of subframes and the Transport Block Size (TBS) used for the downlink transmissions can be dynamically changed by the user through the command line.

The `npdsch_ue` example acts as the counterpart and provides a PHY-only UE that receives and decodes the DL transmission of the eNB.

## IV. Performance Evaluation

This section evaluates the achievable downlink throughput in NB-IoT. We carry out a theoretical analysis first before comparing the results with experimental data obtained from our NB-IoT implementation.

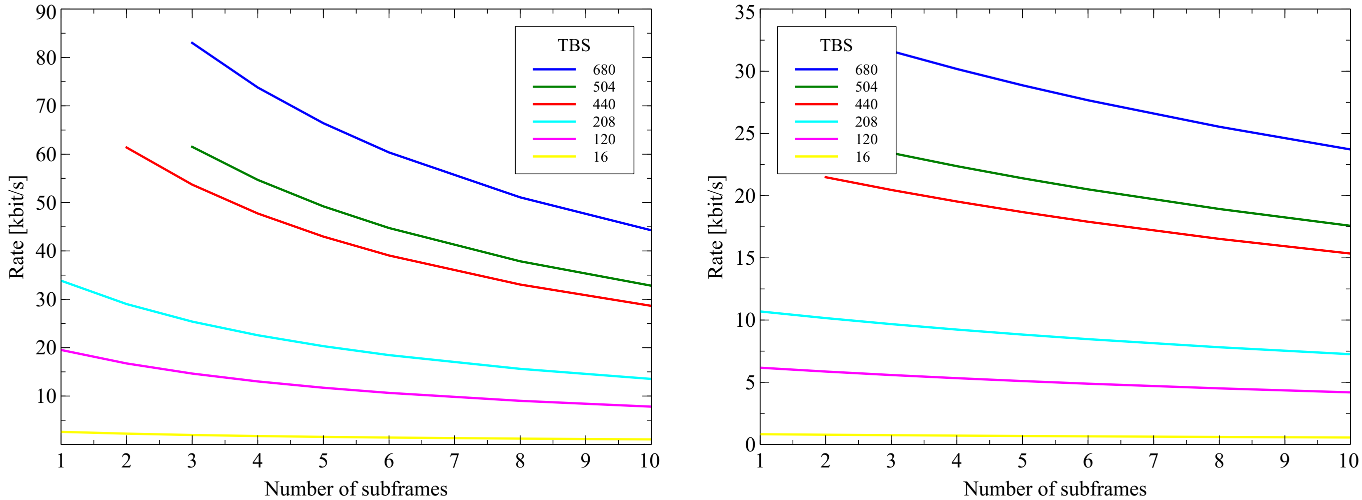
### A. Theoretical Analysis

As for normal LTE, data to be transmitted at the physical layer in NB-IoT needs to have a size of a so-called transport block (TB). The transport block size (TBS) for the DL ranges between 16 and 680 bits. Depending the configuration, a single TB may be carried by one or more subframes. Transporting the largest TBS of 680 bits requires at least 3 subframes. Therefore, the often stated peak data rate in the DL is 226 kbit/s. This value, however, is only of a theoretical nature as it doesn't include the overhead associated with any NPDSCH transmission (except for SIB transmissions). This overhead includes at least one subframe for the NPDCCH to carry the DL grant as well as a minimum of 4 empty subframes that allow the UE to receive and decode the grant and to prepare for the reception of the actual NPDSCH. In total, at least 8 ms are needed to transmit the full TB carrying 680 bits. Please note that in NB-IoT there can only be a single hybrid automatic repeat request (HARQ) process running at the same time. Therefore, interleaved NPDCCH/NPDSCH transmissions are not possible. We also assume only a single transmission of each NPDSCH, i.e., now repetitions. This results in a maximum achievable DL data rate in unacknowledged mode (UM) of 85 kbit/s. Depending on the actual scheduling constraints of the eNB and the number of subframes and repetitions for the NPDSCH, this number may be much lower in reality. Figure 3(a) shows the maximum achievable DL rates for a single UE in UM for a number of TBS sizes as a function of the number of NPDSCH subframes. Note that because not all TBS sizes are possible for every number of subframes, we selected the closest possible value for each configuration in order to make the results comparable to each other.

In acknowledged mode (AM), the actual achievable rate reduces even further than in UM because there is an extra gap between the NPDSCH (data) and the NPUSCH (acknowledgement) transmission of at least 12 subframes. Therefore, even in the best case, at least 21ms are required to transfer 680 bits worth of data, resulting in a maximum rate of 32,38 kbit/s. This again assumes a single NPDCCH subframe for the grant, a 4ms gap, 3 subframes for the NPDSCH, a 12ms gap and one subframe carrying the NPUSCH with the acknowledgement. Figure 3(b) plots the maximum achievable DL rate for a single UE in AM for a number of TBS as a function of the number of NPDSCH subframes.

### B. Experimental Results

After the theoretical analysis, this section will now assess the performance of our prototype implementation and compare it against them. In practice, the above stated results (e.g., 85 kbit/s DL throughput) can only be achieved if the channel conditions between eNB and UE are excellent and the eNB is actually able to schedule transmissions for a specific UE using the minimum number of subframes to, e.g., transmit 680 bit of data in 8 subframes only. Using a single NB-IoT downlink




(a) Unacknowledged mode (UM).

(b) Acknowledged mode (AM).

Fig. 3: Maximum achievable DL rate for a single UE

carrier, however, this is difficult to achieve because the so-called anchor carrier requires specific subframes to be filled with periodic information, such as synchronization signals (i.e. NPSS and NSSS) as well as system information messages (i.e., MIB and SIBs). Those signals will always have higher priority as scheduling grants and user data carried over NPDCCH or NPDSCH, respectively. Our basic NB-IoT eNB example therefore uses a simple static resource allocation scheme in which a NPDCCH containing a DL grant is transmitted in subframe 1 of each frame and the corresponding NPDSCH from subframe 6 onwards in the same frame. Using this configuration allows us to transmit 680 Bits of data in subframe 6, 7 and 8 of each frame, i.e., every 10ms. Hence, using this resource allocation scheme, the maximum achievable DL rate is 68 kbit/s. Figure 4 shows the results of an experiment to assess the maximum achievable DL rate of our prototype implementation. The experiment was carried out under favourable radio conditions with an SNR of approximately 20 dB. We ran the experiment with three different NPDSCH configurations, i.e., with one, two, and three subframes. For each configuration, we also varied the TBS size from minimal to maximal setting ($i_{tbs}$) value. In total, we ran 36 experiments. Each run lasted about one minute, until the measured rate stabilized. From the plot it can be seen that in a high SNR regime with a NPDSCH bit error rate of 0%, the experimental results exactly match the theoretical calculation for each TBS. We are currently executing a set of simulations and experiments to evaluate the DL rate under lower SNR regimes.

## V. Exploring Commercial Deployments

Several network operators around the world have chosen to adopt NB-IoT for MTC communication. Vodafone, for example, began to roll out their network in Spain in late January 2017, starting in Madrid and Valencia, but already announcing the expansion to other Spanish cities, such as Barcelona, Bilbao, Mlaga and Seville [5]. Only days later, on February 1st, we discovered a live NB-IoT carrier in downtown Barcelona in Vodafone's 800 MHz frequency band, which has been used from then on to test and validate standard

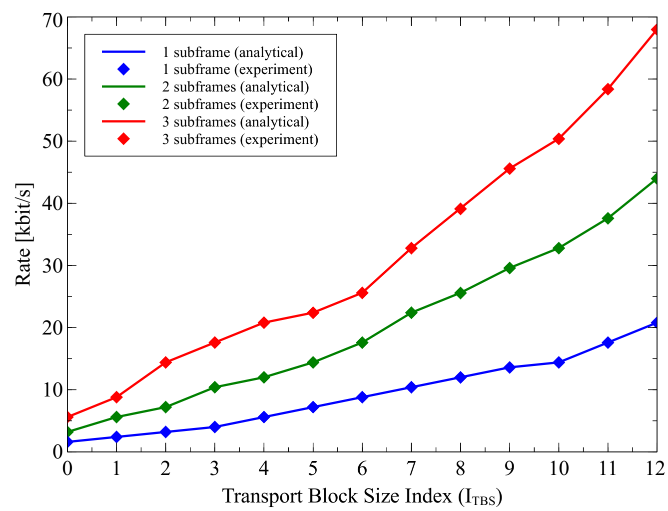



Fig. 4: Comparison of theoretical and experimental DL rate (20 dB SNR).

conformance of our implementation.

Figure 5 shows a power spectral density and waterfall plot of the aforementioned Vodafone LTE band centered at 806 MHz over the full cell bandwidth of 10 MHz. The NB-IoT carrier is clearly visible on the left-hand side of the spectrum. It is transmitted with slightly higher power than the rest of the LTE signal. Because the NB-IoT carrier is embedded in and uses resources of an existing LTE cell, it is said to operate in *in-band* mode.

During Mobile World Congress (MWC) 2017, SRS showcased a fully functioning DL receiver and decoder for NB-IoT. This demonstration not only decoded the live transmission of the Vodafone cell but also displayed various information about the signal, such as the Carrier Frequency Offset (CFO), Sample Frequency Offset (SFO) and Block Error Rate (BER) of the NPDSCH.

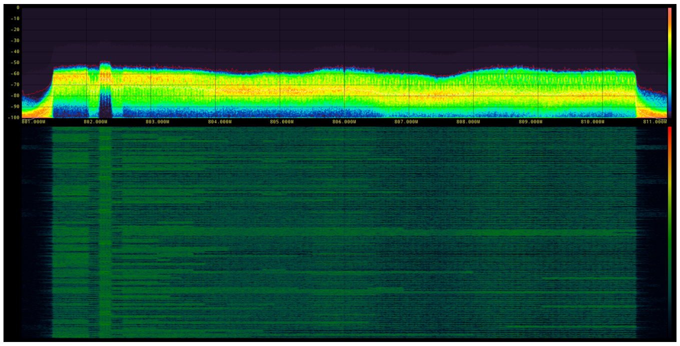


Fig. 5: Waterfall plot of the 10 MHz Vodafone cell at 806 MHz in Barcelona, Spain with the NB-IoT carrier clearly visible in the left part of the signal.

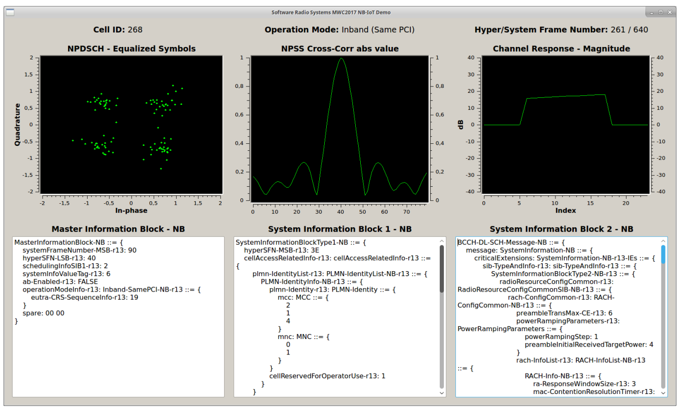



Fig. 6: Screenshot of the NB-IoT UE shown at MWC2017.

Figure 6 shows the graphical user interface of the UE displaying the constellation diagram of NPDSCH (upper left image), the correlation peak of the NPSS (upper middle image) and the channel response (upper right image). The UE also shows the content of MIB, SIB1 and SIB2 (bottom three text fields in Figure 6).

## VI. Conclusion

With the finalization of Release 13 of the LTE Advanced Pro specification in June 2016, 3GPP has provided a new radio access technology based on LTE to address the requirements and challenges of the Internet of Things.

In this paper, we have summarized our efforts in developing a software implementation containing all relevant DL and UL channels and signals defined in the standard as well as example applications that facilitate testing and experimenting with this new technology.

Furthermore, the paper also described experiments carried out to assess the performance of the implementation and compares the obtained results with our analytical model. Our analysis showed that the theoretical peak data rate of 226 kbit/s in the DL cant be achieved in practice due to the control overhead associated with any transmission. In fact, the maximum achievable DL data rate for a single UE is 85 kbit/s in unacknowledged mode and 32.38 kbit/s in acknowledged mode, which can only be achieved with the highest modulation and coding scheme, using the lowest number of subframes and no repetitions. The maximum UL rate of 68 kbit/s achieved in our experiments can be viewed as an realistic upper limit in single carrier deployments. The 20% reduction compared to the theoretical maximum can be well explained by the overhead caused by the periodic DL transmissions, i.e., synchronization signals and system information messages.


## Acknowledgments

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