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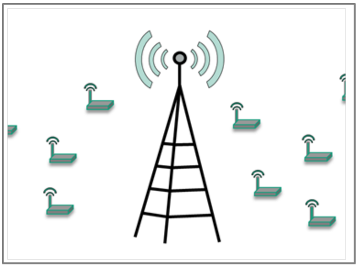
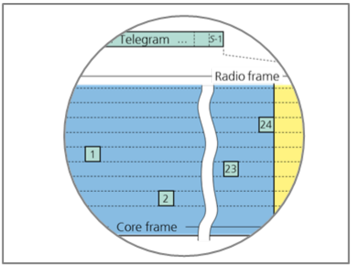
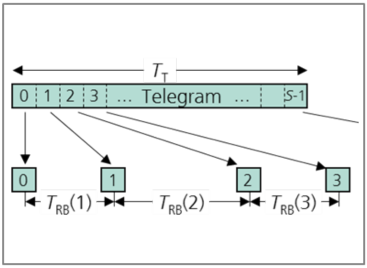
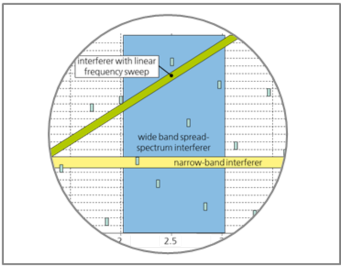
MIOTY^{TM} – PHYSICAL LAYER TECHNOLOGY

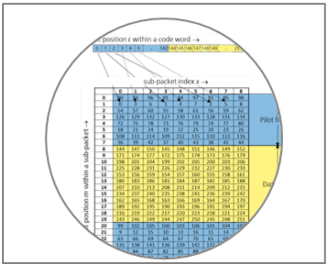
TELEGRAM SPLITTING AS A GAME CHANGING TECHNOLOGY FOR THE FUTURE OF LPWAN

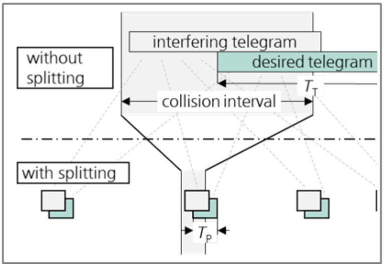












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Low Power Wide Area Networks (LPWAN) have emerged as a new wireless networking solution that aims to realize the Internet of Things (IoT) vision by addressing critical communication challenges of data throughput, power efficiency, coverage, cost and scalability. Capitalizing on cutting-edge qualities of LPWAN with advanced enhancement on network performance, the MIOTY™ (= My IoT) Technology delivers industry-grade connectivity that satisfies the most demanding (Industrial) IoT requirements.

MIOTY™ is a Low Power Wide Area Network solution dedicated for private IoT Networks. MIOTY™ technology introduces a completely new wireless communication protocol with a modern physical layer designed from ground up to withstand interferences and maximize quality of the wireless link. Enabling massive edge data collection at the start of the IoT value chain, the MIOTY™ technology fuels unprecedented real-time data input to the most powerful cloud analytics and application platforms to empower business intelligence. MIOTY™ implements the Fraunhofer IIS Telegram Splitting technology defined as TS-UNB in the ETSI Standard TS103357 to provide unrivalled robustness against interferences and to maximize overall system capacity through extremely short »on air« times.

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1 MIOTY™ in a Nutshell

1.1 The MIOTY™ LPWAN System

Designed for large-scale IoT applications that entail massive battery-operated sensors, the MIOTY™ system employs Ultra Narrow Band communication to transmit low data rate messages (500 bit/s) over long distance (5 km in urban and up to 15 km in rural area). With very narrow signal bandwidth (2 kHz), and cutting edge communication technology the system enables maximum spectrum efficiency for best-in-class spectrum utilization.

The MIOTY™ architecture portrays a star network with at least one central gateway gathering messages from thousands of sensor nodes. The system operates in worldwide license-free sub-GHz bands (915 MHz – North America and 868 MHz – Europe). One individual gateway is able to aggregate over 1,500,000 messages/day or 65,000 messages/hour using only 200 kHz bandwidth, providing unrivalled network capacity and scalability.

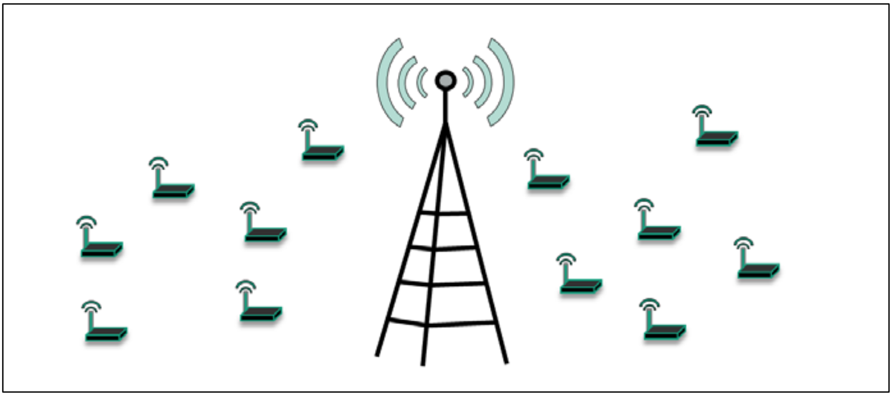


Figure 1: Typical LPWAN technology with thousands of sensor nodes

Compared to alternative LPWANs, MIOTY™ networks guarantee a significantly higher level of robustness against interferences from its own and other co-existing systems leveraging the Fraunhofer IIS's Telegram Splitting technology. Unparalleled interference immunity promises high reliability of data connection in a typically crowded license-free spectrum, securing excellent quality-of-service.

In addition to interference immunity, Telegram Splitting optimizes overall system capacity and greatly reduces power consumption through extremely short »on-air« times. Power supply requirements for the transmitters are therefore considerably simplified, allowing for adoption of inexpensive batteries with minimal maintenance effort. An overview followed by further in-depth technical explanation of how Telegram Splitting technology functions will be provided in Chapter 2 and 3.

Remaining exclusively a software solution, MIOTY™ deliverables consist of two key components: the MIOTY™ sensor node software and the MIOTY™ base station software. With a vendor-neutral configuration, today MIOTY™ software supports a wide range of commercially available, off-the-shelf-hardware, granting end users with maximum flexibility and minimum complexity in designing their cost-effective IoT architecture.

- The MIOTY™ sensor node software is a general-purpose software library enabling easy integration in end customer products for immediate setup of low-cost, high performance »smart devices« at the edge. The library is optimized for power efficiency and runs on low-computing microcontrollers.
- The MIOTY™ base station software is able to run on many industry-standard IoT gateways (e.g. Intel Core i3) connected with a Software Defined Radio frontend (e.g. SDRplay RSP2 pro). It transforms the gateway into a Big Data Aggregator collecting data packets from massive transmitters staying within up to 15 km radius. The software also provides seamless integration with third-party cloud platform for data computing and analytics.

Addressing the most significant drawback of LPWANs that prevents widespread adoption and scalability on a global scale – the lack of standards, Fraunhofer IIS is actively driving standardization activities to realize MIOTY™

technology as an open and worldwide standard for low power wide area communication.

Overview of MIOTY™´s technical key qualities:	
Huge network capacity	up to 1,500,000 messages/day
Extensive transmission range	up to 15 km in flat terrain up to 5 km in urban centers
Minimal power consumption	up to 20 year battery lifetime
Unique mobile communication	nodes operate at up to 120 km/h velocity
Quality-of-service	high interference immunity in a crowded spectrum, deep indoor penetration and multi-layer security
Worldwide operation	global license-free sub-GHz band
New standard	ETSI standard TS 103357 published in June 2018

1.2 What makes MIOTY™ Technology so Unique

MIOTY™ differentiates itself from alternative LPWAN solutions with a unique system design powered by Telegram Splitting technology.

Network reliability challenge in traditional LPWANs

Utilizing 100 kHz bandwidth, current Sub-GHz wireless solutions are able to transmit each message package in a very short period of time (around 5 milliseconds) but only over limited distance of several hundred meters up to 1-2 kilometers. To surpass this problem of short range communication, traditional LPWANs adopting Ultra Narrow Band or Chip Spread Spectrum technologies increase message transmission time to achieve higher network range and coverage.

Longer transmission time, nevertheless, imposes a considerable challenge of connection quality as each message is significantly vulnerable to interferers due to its long »on air« time (at least 1 second and more). Interferers are typically signals by other wireless technologies operating in the same frequency and threat to disrupt data connection between the transmitter and the gateway. In the license-free spectrum utilized by most LPWANs, interference level is particularly high owing to large amount of co-channel wireless connectivity. Network quality of traditional LPWANs is thus greatly impaired.

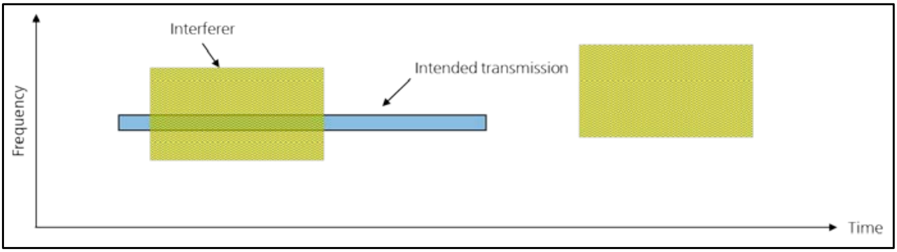


Figure 2: Interferer disrupting intended transmission

Telegram Splitting solution

Combining Ultra Narrow Band technique with the unique Telegram Splitting technology, the MIOTY™ system delivers unrivalled robustness to overcome the challenge of network quality suffered by traditional LPWANs. Instead of transmitting the whole message in one piece as in alternative systems, Telegram Splitting breaks each packet (a telegram) into numerous sub-packets and distributes them over time and frequency. The transmission time of each sub-packet is greatly reduced to only 15 milliseconds with transmission free periods in between, allowing for much higher immunity against interferers from its own and other radio systems in the open spectrum.

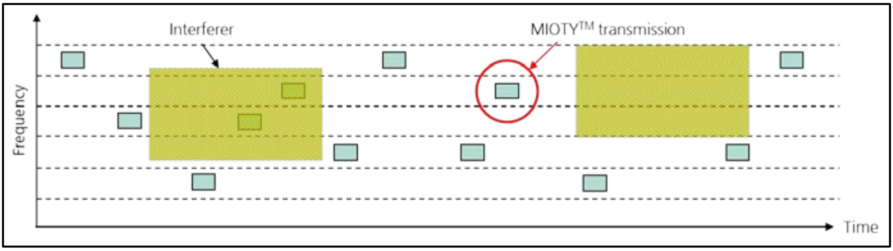


Figure 3: Reducing interferer collision probability by distributing sub-packets using telegram splitting technology

Further enhancing network reliability, superior channel coding with forward error correction (FEC) compensates for up to 50% loss of sub-packets. This means even if half of the sub-packets are disturbed by interferers during transmission, the complete message can still be successfully retrieved at the gateway. This exceptional system design powered by Telegram Splitting offers unmatched quality-of-service for critical Industrial IoT applications where network quality is of highest priority.

Uplink and downlink transmission rates

The Telegram Splitting technology enables high transmission rates in low duty cycle limited bands. Some transmission rate examples related to the message size are listed in Table 1.

Uplink transmission rate for end point duty cycle of 1%		
Message size	**On-air time**	**No. of messages per hour**
10 Byte	363 ms	99
50 Byte	968 ms	37
200 Byte	3236 ms	11
Downlink transmission rate for base station duty cycle of 10%		
Message size	**On-air time**	**No. of messages per hour**
ACK only	106 ms	> 80.000
ACK + 10 Byte Data	398 ms	> 20.000
ACK + 50 Byte Data	1059 ms	> 8.000

Table 1: Transmission rates in up- and downlink related to the message size

Low power operation

The MIOTY^{TM} technology is also optimized for power efficiency. Some transmission rate examples that can be achieved with a size AA battery (2200mAh) and 10 years operating time can be seen in Table 2.

Message size	**On-Air-time**	**Charge**	**Reporting rate***
10 Byte	363 ms	5 µAh	1 Message every 15 min
50 Byte	968 ms	13,5 µAh	1 Message every hour
200 Byte	3236 ms	45 µAh	1 Message every 2 hour
*Assumptions: TX current: 45 mA; Sleep current: 2µA; Battery Self Discharge: <1% per year			

Table 2: Transmission rate related to battery size AA

2 Overview of the Telegram Splitting Ultra Narrowband Standard (TS-UNB)

Telegram Splitting Ultra Narrowband (TS-UNB) approach as defined in the ETSI standard TS 103 357 is a packet-oriented radio transmission protocol designed for wide area networks with star topology. The end devices in such networks are typically transmitting short data packets in irregular time intervals, where the time between two packets is significantly larger than the transmission time interval and may vary over time. The transmission is in general asynchronous, i.e. there is no coordination between the end devices with respect to their transmit time instants. Additionally, the carrier frequency has typically a significant deviation from the nominal frequency, because low cost oscillators are used to keep the cost for an end device low.

The core device of the star network is the base station. Its main task is to receive, detect and decode the radio packets from many end devices distributed within the receiving area of the base station. Due to the asynchronous transmit times some packets may collide, i.e. they overlap in time and frequency at the base station location such that at least one of them or even all are not decodable any more.

The air interface of TS-UNB is designed to mitigate the effects of these undesirable but unavoidable events as much as possible, which makes it especially tailored for applications where a large number of devices are to be served by a single base station, i.e. for high capacity networks. The key technology for achieving this is telegram splitting, a novel and unique feature among today's systems of this type. Its concept was first invented by Fraunhofer IIS and published in [1]. The basic idea is to split a telegram (including header and pilot symbols) into many short pieces, called sub-packets and to transmit them separately over time as short radio bursts with transmission-free intervals in between. Since telegram splitting characterized the way, how an end device accesses the radio resource, it is appropriate to call it Telegram Splitting Multiple Access (TSMA). In order to maximize the gain over classical telegram transmission, TS-UNB combines telegram splitting with slow frequency hopping, strong channel coding for forward error correction (FEC), interleaving and a high degree of virtual randomness with respect to the transmit time instants of the sub-packets and the frequency hopping patterns.

In many applications like telemetry the devices are only transmitting. Some other applications, however, may require controlling the end devices remotely. For these cases, the end devices also incorporate a receiver section to receive device-specific control commands from the base station. TS-UNB provides the basis for both, unidirectional and bidirectional communications between the base station and the end devices. In order to keep the power consumption for the signal processing in the end devices as low as possible, the time interval of reception is coupled strictly to the last transmission time such that the receiver needs to open its receive window only for the minimal necessary time to receive the sub-packets of a telegram. Additionally, the carrier frequencies of the downlink radio bursts are matched to the local oscillator of the end device, such that frequency correction is not necessary. For very low complexity receivers, the TS-UNB provides special synchronization bursts.

The following description treats the transmission directions separately. Following the common terminology in mobile radio systems, the direction from an end device to the base station is called the uplink and the direction from the base station to an end device is called the downlink.

The telegram length is matched to the amount of information to be transmitted. In TS-UNB, the payload on the physical layer may range from 1 to 255 bytes. The shortest telegram in the uplink can carry up to 20 bytes of information.

It follows an introduction into telegram splitting and a detailed description of the signal processing chain from the MAC-layer data unit to the RF-signal.

3 Telegram Splitting: Concept and Benefits

3.1 Concept of Telegram Splitting

A key concept of TS-UNB approach for achieving a high network capacity is telegram splitting – a novel and unique feature among all state-of-the-art systems of this kind. As illustrated in Figure 4 a telegram of duration T_T is split into a number S of equally sized pieces, called sub-packets of duration T_T/S. After modulation and conversion to the RF carrier frequency these sub-packets appear as time-limited RF-signals. The TS-UNB standard uses the term **sub-packet** for the logical entity before modulation containing bits and bytes and the term **radio burst** for the time-limited modulated RF-signal carrying the content of a sub-packet.

In order to introduce a kind of randomness, the time interval between the transmissions of any two consecutive radio bursts may depend on the radio burst index or sub-packet index $s = 0,1,\ldots,S-1$. In Figure 4, $T_{\mathrm{RB}}(s)$ denotes the time interval from the center of radio burst $s-1$ to the center of radio burst s. The sequence $T_{\mathrm{RB}}(1), T_{\mathrm{RB}}(2), \ldots, T_{\mathrm{RB}}(S-1)$ is called the radio burst transmit time pattern or for short **time pattern**.

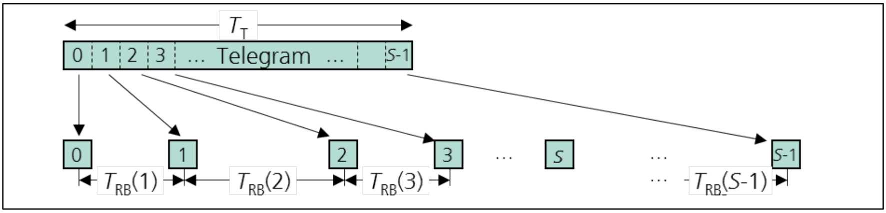


Figure 4: The concept of telegram splitting

The TS-UNB approach uses telegram splitting in combination with slow frequency hopping as illustrated in Figure 5. The carrier frequency changes from radio burst to radio burst within a given bandwidth. In order to be independent of a specific carrier frequency, indices of the form $C_{\mathrm{RB}}(s) \in \{0,1,2,\ldots\}$ are introduced to identify the carrier frequency for sub-packet s. Let f_0 be the nominal carrier frequency of carrier index 0. Then the nominal carrier frequency of radio burst s can be obtained from

$$f_{\mathrm{RB}}(s) = f_0 + C_{\mathrm{RB}}(s)B_{\mathrm{C}} \tag{1}$$

where B_{C} is the carrier spacing. For the standard mode of the TS-UNB profile the number of different carrier frequencies is limited to 25 and B_{C} is equal to 2,380.371 Hz.

The sequence $C_{\mathrm{RB}}(0), C_{\mathrm{RB}}(1), \dots, C_{\mathrm{RB}}(s), \dots, C_{\mathrm{RB}}(S-1)$ of carrier indices is called the **frequency pattern**. Its combination with the time pattern is called the **time-frequency pattern** or **TSMA-pattern**. It defines the transmission characteristic of a split telegram completely. This pattern must be known a priori to the transmitter as well as to the receiver. Then, the receiver can reconstruct the telegram easily from the received radio bursts.

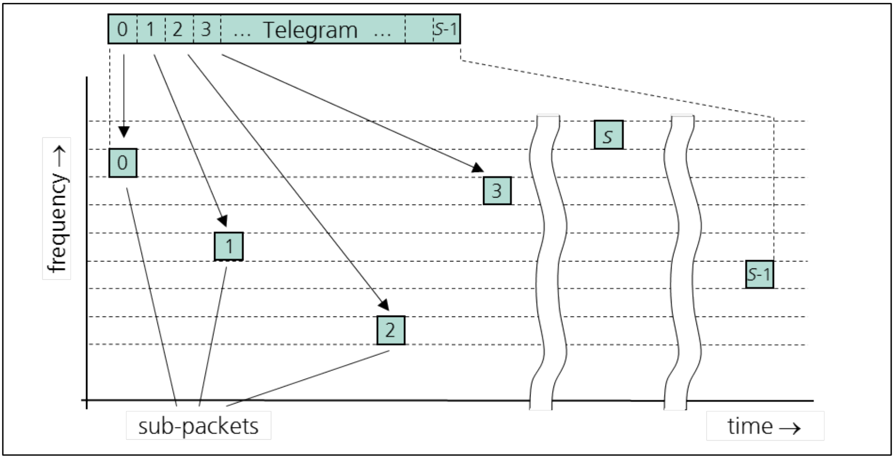


Figure 5: Telegram splitting combined with frequency hopping

The time window between the first and the last radio burst is called a **radio frame**. The full RF-bandwidth allocated for the operation of a TS-UNB system is called a radio channel. The bandwidth of this channel includes the frequency spread of the 25 carrier frequencies for the radio bursts as well as the maximal tolerances of the local oscillators.

3.1.1 TS-UNB Uplink

In the uplink, i.e. the transmission from the end device to the base station, the shortest telegram has a fixed length of 186 bits and can carry up to 160 bits payload. After channel coding and interleaving the telegram is split into 24 sub-packets. The sequence of 24 radio bursts carrying the information of this shortest telegram is called the **core frame**. For each additional payload byte, another radio burst is transmitted. The sequence of these additional radio bursts is called the **extension frame**. This concept is visualized in Figure 6. Irrespective, how many bytes are transmitted, the core frame is always transmitted and the receiver can obtain the telegram length from the information available in the core frame exclusively.

For the uplink, the TS-UNB specification contains two groups with eight fixed time-frequency patterns each and a 3rd group with only one time-frequency pattern transmission with low delay requirements. Figure 7 visualizes a time-frequency pattern from the 1st group. The 1st group is used for the normal operation. The 2nd group is only used, if re-transmission is applied.

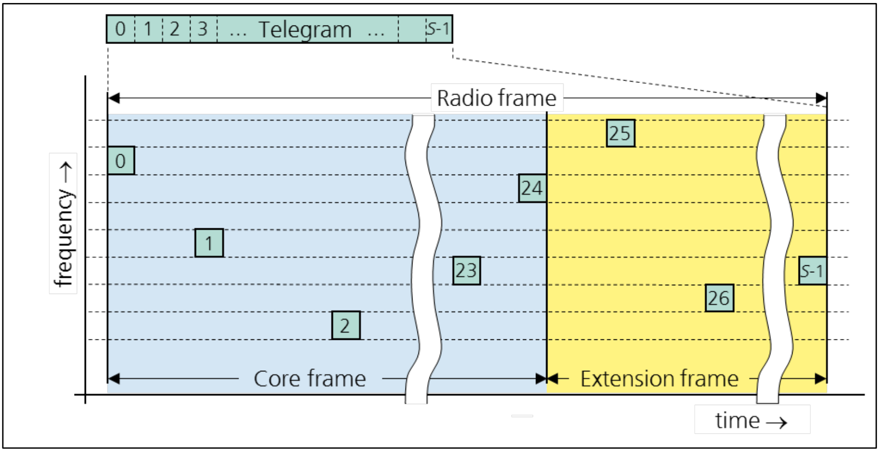


Figure 6: Subdividing an uplink radio frame into a core frame and an extension frame

On one side this small set limits the number of patterns the base station must search for, on the other side it enables to introduce sufficient randomness such that the probability of collisions of two telegrams approaches zero. Collisions of radio bursts are not so critical, since a strong channel code allows reconstructing the whole telegram, even if more that 50% of the radio bursts are lost.

Without going into details, a few common characteristics of the specified time-frequency patterns for the core frame shall be mentioned.

- Within the occupied spectrum 25 carrier frequencies are defined from which 24 are used for the core frame and all 25 are used for the extension frame.
- Each carrier frequency is used once per pattern. This implies that there are no collisions of the radio bursts from two telegrams that use the same time-frequency pattern as far as the time shift against each other is larger than the radio-burst transmit interval.
- The patterns are designed for a minimal number of mutual radio burst collisions. To be concrete: Whenever two end devices are using different time-frequency patterns of the same group, and their relative time-shift is in the range of -3.6 to +3.6 seconds (out of this interval there are no collisions anyway), in not more than 3.3% of the time shifts collisions occur, where in most cases only 3 radio bursts are affected at a time.
- The transmission-free time intervals between any two radio bursts are all longer than 300 symbol intervals corresponding to 126 ms.

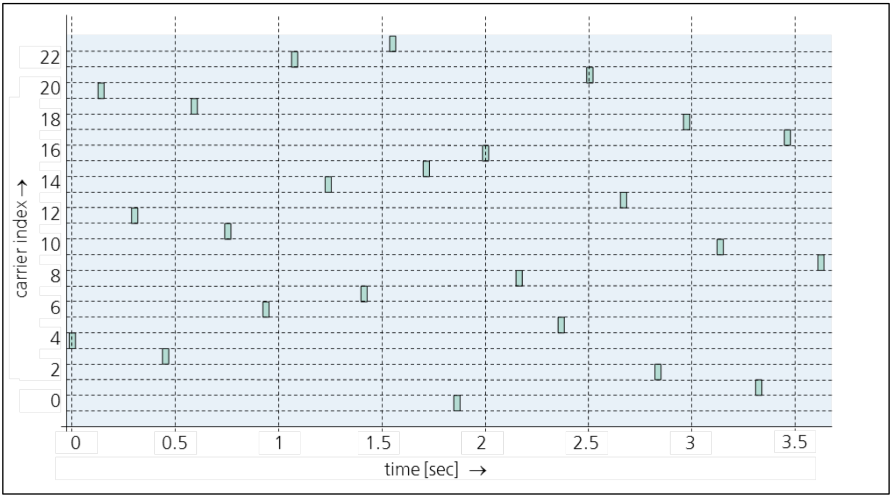


Figure 7: Example of a time-frequency pattern for the TS-UNB uplink core frame

In contrast to the core frame the extension frame does not have a fixed time-frequency pattern. Instead, an algorithm is specified how to generate a pseudo-random pattern from some header information contained in the core frame. The algorithm guarantees also here, that the transmission-free time intervals between any two radio bursts are all longer than 300 symbols.

The TSMA-parameters of the TS-UNB uplink are summarized in Table 3. For more details refer to chapter 4.

The specification allows two different modes of operation, distinguished by their symbol rates: 2,380.371 and 396.729 symbols per second. Both can be easily derived from a 26 MHz clock. The higher rate is 6 times the lower rate. The lower rate mode is called the extended range mode (ER-mode) because the transmitted energy per bit is 6 times higher than with the higher rate, which is called the ultra-low power mode (ULP-mode). Their main parameters can be obtained from Table 3.

Mode of operation:	**Ultra-low power (ULP)**	**Extended range (ER)**
Modulation symbol rate	2,380.371 symb/sec	396.729 symb/sec
Radio burst duration	15.12 msec	90.74 msec
On-air-time per core frame	0.363 sec	2.18 sec
Core frame time interval:		
Normal (pattern group 1&2):	< 3.7 sec	< 22.2 sec
Short (pattern group 3):	< 0.766 sec	< 4.6 sec

Bandwidth:		**Narrow**	**Standard**	**Wide**
Radio bursts per core frame		24		
Radio bursts per extension frame		0 … 235		
Number of carriers per TSMA-pattern:	**Core frame:**	24		
	Extension frame:	25		
Carrier spacing B_C		396.729 Hz	2,380.371 Hz	28,564.453 Hz
Occupied channel bandwidth (excl. oscillator tolerances)	**ULP:**	11.9 kHz	59.5 kHz	688 kHz
	ER:	9.9 kHz	57.5 kHz	686 kHz
Required channel band-width (incl. 20 ppm oscillator tolerances)		25 kHz	100 kHz	725 kHz

Table 3: Uplink TSMA-parameters

Depending on the available bandwidth, both modes can operated as narrow, standard or wide. Although each rate can be combined with narrow, standard or wide, the intention is to use the slow symbol rate for the narrow mode only and the higher symbol rate for the standard and wide mode. Any numeric example in this description refers to the standard mode in combination with the higher symbol rate, if not otherwise stated. The used frequency band depends on the available spectrum for short range devices and can be adapted to the local requirements.

In any case, if two bands are available, e.g. 2 x 100 kHz, these are used in a special way to further increase the transmission reliability. More details about the uplink can be found in chapter 4.

3.1.2 TS-UNB Downlink

Whenever a second radio channel with a bandwidth similar to the uplink channel is available, it is used for the downlink. If this is not available, the downlink can use the same channel as the uplink. But this should be avoided, whenever possible, because it degrades the system performance in a heavily loaded network.

As for the uplink, also for the downlink the radio frame is subdivided into a core frame and an extension frame. The core frame consists of 18 radio bursts, where the first 9 radio bursts are already sufficient to transmit the complete core frame message and the remaining 9 radio bursts can optionally be used to retransmit the same message in order to increase the transmission reliability. If additional data is to be transmitted, an extension frame is appended. The extension frame is sub-divided into 1 to 11 blocks with 18 radio bursts each. It uses the same time-frequency pattern as the core frame.

For the downlink, the TS-UNB specification contains 8 fixed time-frequency patterns from which one is to be selected per downlink message. In order to introduce some kind of randomness, the pattern is selected on the basis of information received from the previous uplink telegram. For details see section 5.2.2.

The TSMA-parameters of the TS-UNB downlink are summarized in Table 4.

Bandwidth	**Narrow**	**Standard**	**Wide**
Radio bursts per core frame	18		
Radio bursts per extension frame	$n_b \cdot 18$ with $n_b = 0,1,2,\ldots,11$		
Number of carriers per TSMA-pattern	24		
Carrier spacing	396.729 Hz	2,380.371 Hz	28,564.453 Hz
Occupied bandwidth per radio frame (oscillator tolerances excluded)	11.5 kHz	57.1 kHz	659.4 kHz
Required channel bandwidth (incl. 20 ppm oscillator tolerances)	25 kHz	100 kHz	725 kHz
Modulation symbol rate [symb/sec]	2,380.371		
Radio burst duration			
core frame	11.76 ms		
extension frame	11.76 … 21.43 ms		
On-air-time per core frame	0.106 sec (0.212 sec if repeated)		
Core frame time interval	< 3.7 sec		

Table 4: Downlink TSMA-parameters

The specified downlink time-frequency patterns have the following common characteristics:

- Within the occupied downlink spectrum 24 carrier frequencies are defined.
- All radio bursts of any time-frequency pattern are transmitted on distinct carrier frequencies. This implies that there are no radio burst collisions between any two telegrams that use the same time-frequency pattern as far as the time shift against each other is larger than the radio burst length.
- The patterns are designed for a minimal number of mutual radio burst collisions. To be concrete: Whenever two end devices are using different time-frequency patterns, and their relative time-shift is in the range from

-3.6 to +3.6 seconds (out of this interval there are no collisions anyway), in not more than 5.5% of the time shifts collisions occur, where in most cases only 1 radio burst is affected.

- The transmission-free time intervals between any two radio bursts are all longer than 400 symbol intervals corresponding to 168 ms in the standard mode.

3.1.3 Sub-Packet Structure

The sub-packets are the basic transmission elements. Once they are modulated and mapped to time-limited RF-signals they are referred to as radio bursts.

In the TS-UNB uplink all sub-packets have the same size and structure as shown in Figure 8. They consist of 24 coded data bits and 12 pilot bits in the center. The pilot field is filled with one of two fixed pilot patterns. One is used for sub-packets of the core frame and the other for sub-packets of the extension frame. More details can be found in section 4.2.4.

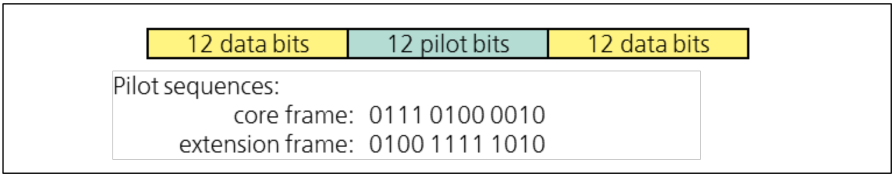


Figure 8: Sub-packet structure in the TS-UNB uplink

In the downlink the sub-packets consist of 16 pilot bits and 12 coded data bits. The pilot sequence is split into two 8 bit sequences according to Figure 9. The core frame uses only sub-packets with the 12 data bits in the center and no further data bits. In the extension frame, up to 12 additional coded bits may be appended to the left and to the right, depending on the actual message length.

The pilot sequences for the sub-packets of the extension frame are fixed. For the sub-packets of the core frame, the pilot bits do not have a fixed pattern. Instead an algorithm is specified how to derive these bits from some information which can be obtained from the uplink core frame. Hence, it is available at the base station and the end device prior to downlink transmission. Details can be found in section 5.2.2.

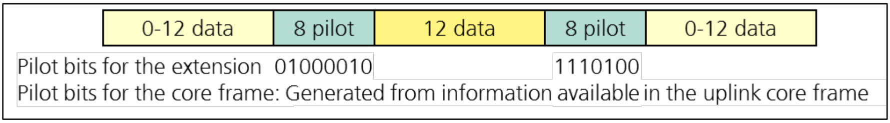


Figure 9: Sub-packet structure in the TS-UNB downlink

At this point it is fair to mention that there is obviously a price to pay for telegram splitting. The price is an increase of overhead in terms of additional pilot symbols. In the uplink TS-UNB uses a 12 bit pilot sequence in a sub-packet which carries 24 bits of (coded) information. This corresponds to an overhead of 50% w.r.t. the coded data symbols. For detecting a telegram which is transmitted as a whole, typically much less pilot symbols are necessary. Assuming 10% overhead for compact telegram transmissions, the loss of telegram splitting due to increased overhead is in the order of 1.3 dB. On the other side, the pilot sequence of 12 bits enables phase estimation with sufficient accuracy such that coherent detection can be applied. Since the radio bursts are very short, this phase estimate can be used for all data of a radio burst. Hence, telegram splitting enables coherent detection at the receiver. This gives a realistic gain of up to about 2.5 dB over non-coherent detection. Taking this into account, the additional overhead results in an overall gain of more than 1.2 dB over non-coherent detection with compact telegram transmission.

3.2 Benefits of Telegram Splitting

3.2.1 Telegram Splitting and System Capacity

Telegram splitting gives more degrees of freedom in system design, which can be exploited to avoid unfavorable telegram collisions. This may become plausible at hand of a simple example scenario.

Consider two devices transmitting periodically telegrams as a whole with a transmission time interval of T_T as illustrated at the top of Figure 10. From time to time the two telegrams may overlap in time such that at least one of them or even both could not be detected any more. Such an event is commonly called an irresolvable collision. Such an irresolvable condition occurs only, if the transmission of the interfering telegram starts within a certain interval w.r.t. to the desired telegram. This interval is referred to as collision interval in Figure 10. If the telegrams do not use forward error correction coding, an irresolvable collision occurs already, when the absolute difference of their transmission start times is less than T_T, i.e. the collision interval is $2\mathrm{T_T}$. Assuming equally distributed start times within the average period T_{Per} of telegram transmissions, the probability of collisions is given by $2T_T/T_{Per}$. If forward error correction coding is applied together with a suitable interleaving scheme, a fractional overlap could be tolerated to a certain extent. For simplicity let us assume that a maximal overlap of up to 50% of the transmission interval T_T could be tolerated. In this case, the collision interval is halved and the probability of severe collisions reduces to T_T/T_{Per}.

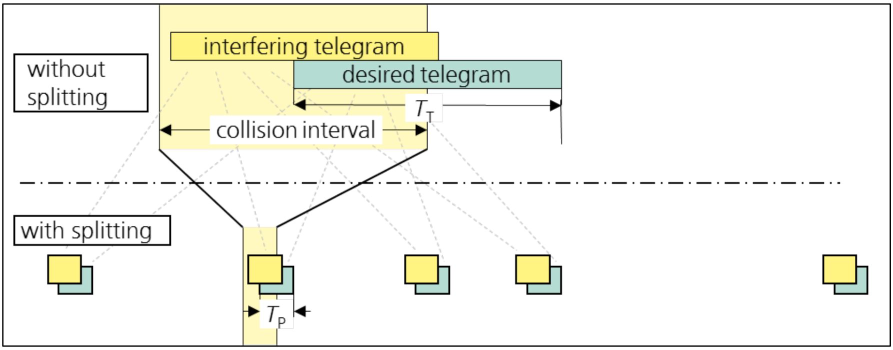


Figure 10: Collision intervals for telegram transmissions with and without splitting

Consider now the same scenario, but let the coded telegrams be split into a number S of radio bursts with varying transmission-free time intervals between the radio bursts as illustrated at the bottom of Figure 10. If the transmission-free time intervals would be equally long, the probability of collisions would be the same as if the telegrams were transmitted as a whole. Only the collision interval would be split into S pieces.

The choice of transmit time pattern is a new degree of freedom which is offered by telegram splitting and which can be utilized to mitigate the effect of collisions. The pattern could e.g. be chosen such that any time shift of the pattern against itself whose magnitude is larger than the radio burst tion T_P leads to at most one sub-packet collision. The error correction capability of the code can easily reconstruct the data of a lost sub-packet such that this doesn't count as an irresolvable collision. An irresolvable collision occurs in the considered scenario with two end devices only, if the absolute time difference of the transmission start times is less than T_P, such that all radio bursts of both telegrams overlap synchronously by more than 50% of their duration. Then, the collision interval is given by $T_P = T_T/S$ as indicated at the bottom of Figure 10. Thus, the probability of irresolvable telegram collisions is reduced by a factor of $1/S$ by telegram splitting.

In order to utilize the new degrees of freedom even more, the TS-UNB specification uses frequency hopping on top of an irregular time pattern. Additionally, they are using not only one, but six different time-frequency pattern for consecutive telegram transmissions in a sequence, which repeats only after 15 telegrams. These features guarantee an extremely low probability that two devices use the same pattern at the same time in the same area.

In a network with a large number of asynchronous devices, radio burst collisions occur almost random and the probability that these collisions cannot be resolved reduces drastically compared to the classical compact telegram transmission. A deeper quantitative analysis reveals that telegram splitting combined with channel coding can significantly increase the transmission reliability and/or the number of devices served by the same base station.

3.2.2 Robustness against Interference from External Systems

Since TS-UNB is expected to work in an ISM-band, where end devices of other systems are also active, it is worth to consider the effects of interferences from foreign systems, for short called external interference. Telegram splitting together with frequency hopping and strong channel coding makes the signal extremely robust against external interference. The MIOTY^{TM} receiver is designed such that the channel decoder can still recover the whole telegram, if more than 50% of sub-packets are lost.

The following characteristics follow immediately from the properties of the time-frequency patterns. The effects from external interferences are illustrated in Figure 11 for different signal characteristics.

- Interference signals shorter than 126 ms affect at most 1 sub-packet per telegram, irrespective of the used bandwidth, because the transmission-free intervals last at least 126 ms (wideband interferer in Figure 11).
- Interference signals with a bandwidth in the order of the TS-UNB channel spacing, i.e. around 2.4 kHz affect at most two radio burst per telegram, irrespective of the transmission time interval (narrowband interferer in Figure 11).
- Systems that use spread spectrum techniques may affect the whole frequency band over a longer time. The effect of their telegrams depend on the kind of spreading technique used:
  - if the spreading is achieved by a signal whose carrier frequency is sweeping relatively slow (with around 150 Hz/ms or even less), the signal occurs as a narrow-band interferer from a TS-UNB point of view, because of the short radio burst transmission interval of 15.1 ms. Consequently, a radio burst may be only affected at random when the sweep frequency and time matches to the time-frequency box used by a radio burst (see interferer with linear frequency sweep in Figure 11)
  - if the spreading is achieved using e.g. PN-sequences or fast frequency sweeping, the interferer power is spread over a large bandwidth, typically as large as or larger than the spectrum band used by TS-UNB profile (wide band spread spectrum interferer in Figure 11). These signals might interfere all TS-UNB frequencies simultaneously, but two facts mitigate their effects significantly:

1. The fraction of the power that falls into the narrow band of a TS-UNB channel is quite low.

2. For the duration of such an interferer the above statement holds: Short telegrams affect only a few radio bursts per telegram.

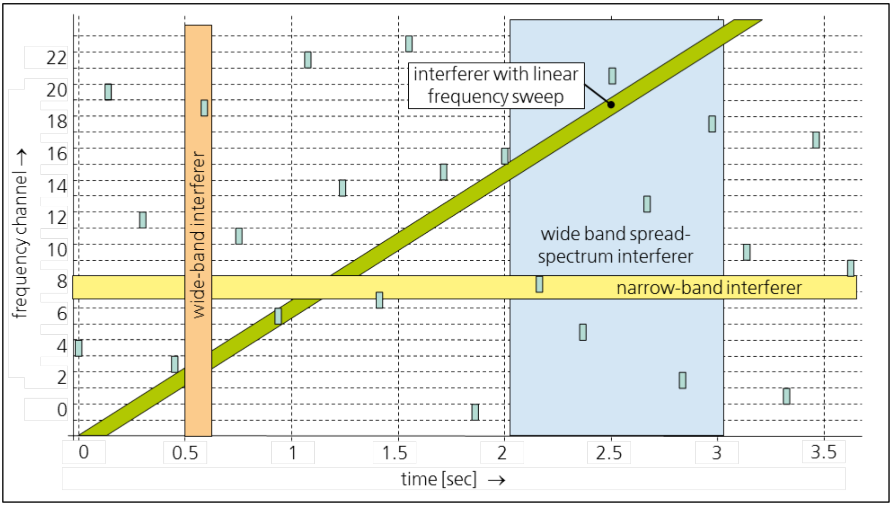


Figure 11: TS-UNB core frame in the presence of different types of interferers

3.2.3 Telegram Splitting and Mobility

The aspect of mobility becomes more and more important for IoT devices. In current applications it’s the base station which might be moving through an area while collecting the data from many devices. But in the near future, also the devices might move as well. The main effect of movements is time-varying fading on the radio path. The speed of fade-changes can be roughly quantified by the Doppler frequency. The maximal Doppler frequency depends on the vehicle speed and the carrier frequency and can be calculated using the well-known relation

$$f_{\mathrm{Dmax}} = \frac{v}{c} f_{\mathrm{c}} \approx 0.926 \frac{v}{\mathrm{km/h}} \times \frac{f_{\mathrm{c}}}{\mathrm{GHz}} \tag{2}$$

where c is the speed of light, f_{c} the carrier frequency and v the speed of the moving device. Generally, a high Doppler frequency is a problem for coherent detection, especially when the packets become longer. In case of telegram splitting like it is applied in TS-UNB the radio bursts are, however, very short.

Since the modulation format is robust against phase estimation errors, even a simple receiver for the ULP-mode can cope with Doppler frequencies of up to $1/(4 \times 0.015) \approx 17\mathrm{Hz}$. For the unlicensed 868 MHz band in Europe this corresponds to a vehicle speed of around 20 km/h. With sophisticated signal processing at the base station's receiver, the speed limit could be significantly raised, thanks to some special characteristics of the TS-UNB signal design. The MIOTY$^{\mathrm{TM}}$ uplink receiver can in fact handle speeds of up to 120 km/h for the ULP-mode.

In the region of low to medium Doppler frequencies, telegram splitting has another advantage compared to compact transmission: Due to the wide time spread of the radio bursts, the fading becomes almost uncorrelated already for Doppler frequencies as low as 1 Hz. Doppler frequencies in this order of magnitude occur at least outdoors nearly everywhere, also in scenarios, where both, the transmitter and the receiver, have a fixed location. This is due to moving objects in the radio propagation environment (like cars and trees in the wind). In combination with strong channel coding and interleaving a high diversity gain can be achieved, thus mitigating the effects of multipath fading almost completely. In fact, the required signal-to-noise ratio for a given quality of detection under flat Rayleigh-fading conditions (assuming independent fading from radio burst to radio burst) is less than 2 dB worse than for a static, non-fading channel. This is another unique advantage of telegram splitting compared to compact transmissions.

4 TS-UNB Uplink Description

4.1 Frame Structure on the Physical Layer

A data frame on the physical layer of the TS-UNB uplink has a structure as shown in Figure 12. It can carry up to 255 bytes of information provided by the MAC-layer. This data packet is called the MAC Packet Data Unit (MPDU). If the MPDU consists of 20 bytes or less, the complete packet on the physical layer has a fixed length of 186 bits including 2 CRC-fields, 1 PSI-field and 2 additional bits for identifying the used MAC-mode.

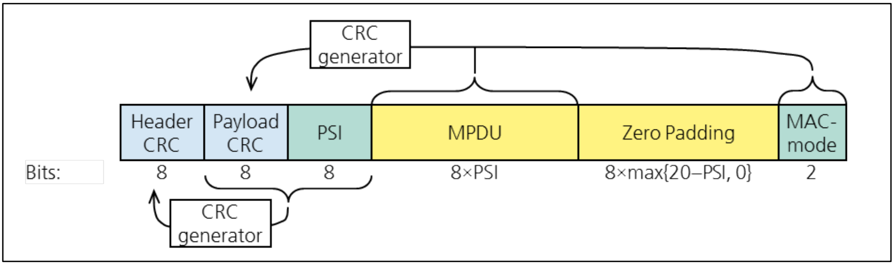


Figure 12: Uplink payload structure on the physical layer

MPDU-field and zero padding

The yellow field is the core field. It is minimal 20 bytes long and it contains the MAC Packet Data Unit (MPDU) and possibly padded zeros, if the MPDU is less than 20 bytes long. If the MPDU has 20 bytes or more it fills the yellow field completely without any additional zero bytes.

PSI-field

The left green field is the Packet Size Indicator (PSI). It is 8 bits long and contains the length of the MPDU in number of bytes. The PSI also indicates whether an extension frame follows or not: If the PSI value is less than or equal to 20, the whole information is contained in the core frame. If it is larger than 20, an extension frame follows.

MAC-mode

The right green field indicates the used MAC-mode. Although the TS-UNB specification includes a MAC-protocol, there may be reasons to use another perhaps proprietary protocol or even no protocol at all. At the time of writing this system description, only two MAC-modes are distinguished:

- 00 indicates the fixed MAC-mode (fixed by the TS-UNB specification)
- 01 indicates any other MAC-protocol. This mode is called the variable MAC-mode.

These two bits together with six tail-bits needed for terminating the convolutional code fill the last byte of the data packet.

Payload-CRC

The blue field named »Payload CRC« contains 8 cyclic redundancy check bits generated from the MPDU and the 2 bits for the MAC-mode, excluding possibly padded zeros. These bits are generated by a linear feedback shift register with 8 binary cells which is fed with the bit sequence.

Header-CRC

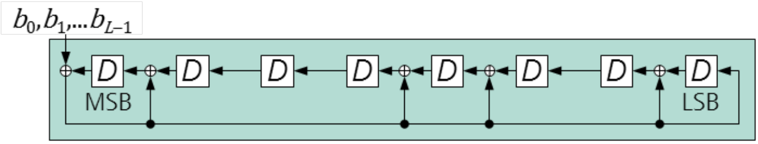
The field named »Header-CRC« contains 8 cyclic redundancy check bits generated from the payload CRC and the PSI.

This two-step procedure for the CRC-bits has a deeper sense:

1. It enables the receiver to do a first error check already after the first 3 bytes have been decoded. If this check fails, the PSI maybe wrong and the remainder of the code word is useless and must not be decoded any more, thus saving computational effort.
2. It allows the receiver to decide very early whether an extension frame follows or not.
3. The information for the time-frequency hopping pattern for the extension frame is derived from these two CRC-bytes (see 4.3.2).

Generation of 8 CRC-bits according to the TS-UNB standard

The CRC-bits for both CRC-fields of the uplink payload are generated by a linear feedback shift register (LFSR) as shown in Figure 13. Initially, the register cells are filled with ones. The sequence of L data bits is fed into the LFSR starting with the most significant bit (MSB) b_0 and ending with the least significant bit (LSB) b_{L-1}. For the generation of the payload-CRC the MSB is the 1st bit of the MPDU-field and for the header-CRC the MSB b_0 is the MSB of the payload-CRC. Each input bit b_l is exclusive or combined with the content of the left-most register cell. If the result is one, the coefficients of the generator polynomial are added modulo-2 to the contents of the corresponding register cells and subsequently left-shifted by 1 step. If the result is zero, the register is only left-shifted by one step and the content of the right-most register cell becomes zero. After L clock cycles the register contains the 8 CRC-bits, where the MSB is contained in the left-most register cell.



Generator polynomial: $g(D) = D^8 + D^7 + D^4 + D^3 + D^1 + D^0 \quad (0x19B)$

Figure 13: CRC-generator for 8 check bits according to the TS-UNB standard (Hint: In the ETSI document, the leading 1 in the hexadecimal representation of the generator polynomial is omitted)

4.2 Signal Processing of the Physical Layer Payload

The complete signal processing chain from the physical layer data packet to the RF-signal in the uplink is shown in Figure 14. The blocks are described in the following sections one by one. In order to simplify the notation, example values refer only to the core frame, containing up to 20 bytes of MPDU. An appended plus-sign shall indicate that the MPDU is longer than 20 bytes.

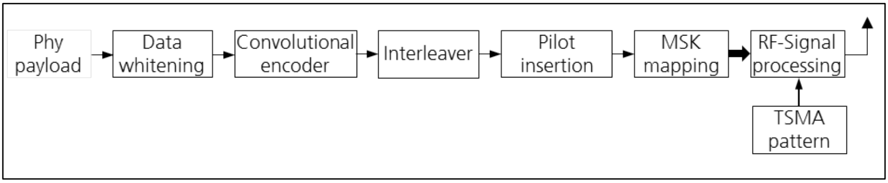


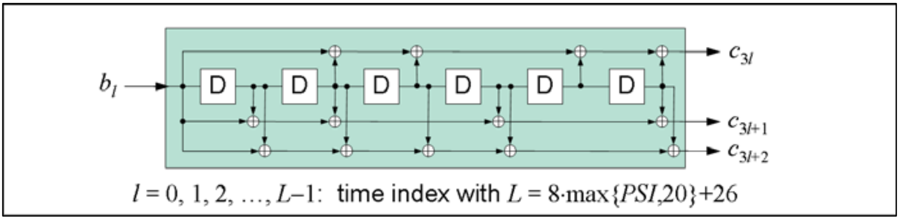
Figure 14: Block diagram of the wave form generation in the uplink

4.2.1 Data Whitening

At first the data of the physical layer frame undergoes a whitening process, i.e. a fixed bit sequence generated by a linear feedback shift register of length 9 is bit-by-bit added modulo-2 to the 186^{+} payload bits from Figure 12. This step is not necessary from a functional point of view, but it reduces the probability of long zero-sequences which occur in case of zero padding and might occur also in the MPDU. The modulo-2 addition of this pseudo-noise sequence guarantees an almost symmetric spectrum of the RF-signal. The PN-sequence is the same for each frame. So it needs to be generated only once for the maximal length of $26 + 8 \times 255 = 2066$ bits, according to IEEE 802.15.4 [3].

4.2.2 Channel Coding for Forward Error Correction

At next, the 186^{+} whitened data bits are mapped to a block of 576^{+} coded bits by a 1/3-rate convolutional code with constraint length 7 with generator polynomials 1101101, 1010111 and 1011111 (in binary notation, 1st coefficient corresponds to last register cell) as shown in Figure 15. In order to terminate the encoder in a well-defined state, 6 zero-valued tail bits are appended to the whitened data block before encoding. The block with 576^{+} coded bits are commonly called a code word. One additional detail shall be mentioned here: Terminated (sometimes also called blocked) convolutional codes have the well-known property that the first and the last bits of the input data experience a lower error probability than the bits in the center of the block. The TS-UNB profile utilizes this inherent unequal error protection property by transmitting the most important bits at the beginning and at the end of a code word.



$l = 0, 1, 2, \ldots, L-1$: time index with $L = 8 \cdot \max\{PSI, 20\} + 26$

Figure 15: Encoder of the 1/3-rate convolutional code with constraint length $L_c = 7$

This encoding step enables the receiver to correct a large amount of transmission errors. The receiver can decode the information of a complete core frame even if more than half of the radio bursts are lost. This, however, is not a merit of strong channel coding alone. The interleaver plays an important role as well.

4.2.3 Interleaving

As convolutional codes are optimal for statistically independent bit errors, but errors typically occur in bursts – especially in the context of telegram splitting – a well-designed mapping from the encoder output to the sub-packets and the bit positions within the sub-packets is required to exploit the full potential of the error correction capability of the convolutional code. This mapping is commonly called interleaving.

At first, the data block of 576^+ coded bits is cyclically shifted by 48 bits such that the last 48 bits become the first 48 bits. It follows a two-step mapping scheme, where

- the 1st step is a mapping to the sub-packets and
- the 2nd step is a mapping to the bit positions within each sub-packet.

The mapping to the sub-packets for the first 288 bits (corresponding to half the number of coded bits in a core frame) differs from the mapping for the remaining part of a cyclically shifted code word.

For the first 288 bits the interleaver is the same for all applications, independent from the code word length. These bits are distributed equally over the 24 sub-packets of a core frame. Let $i \in \{0,2,3,\dots,575,\dots,\}$ denote the bit position in the block of the cyclically shifted code word, and $s \in \{0,1,2,\dots,23\}$ denote the sub-packet index, then the mapping rule is simply given by

$$\boxed{s[i] = i \bmod 24 \text{ for } i < 288} \tag{3}$$

After de-interleaving in the receiver, bit errors within any 24-bit-window appear statistically independent, because they have been transmitted in different sub-packets. This mapping guarantees already that the potential error correction capability of the code can be exploited almost completely.

Using a common interleaving scheme for the first 288 bits for all code word lengths enables the receiver to decode the header information including the PSI already from these bits. This is important, since the header contains all information necessary to decode the remaining part of the core frame and to receive and decode the extension frame. Following the well-known recommendation that the decision delay in a Viterbi-decoder of a convolutional code needs not be larger than $5 \times L_c$, where $L_C = 7$ is the constraint length of the code, the header information can already be derived from the first $3 \times (24 + 5 \times 7) \ = \ 177$ coded bits.

Before describing the mapping to sub-packets for the remaining bits, the 2nd interleaving step is explained.

The 2nd interleaving step is characterized by the rule to fill the sub-packets beginning with the bit positions closest to the pilot sequence and ending with the outer most bit positions (see Figure 8) such that the first bits of the cyclically shifted code word are transmitted close to the pilot sequence. From all possible schemes this kind of mapping has some advantages in fast fading environments, where the carrier phase may change significantly within a sub-packet. In these scenarios the reliability of a symbol decision decays with the distance from the pilot sequence. The placement of the first 200 bits of a code word close to the pilot sequence increases the decision reliability of the header. The cyclic shift places also the last 48 bits of a code word close to the pilot sequence such that the MAC-mode bits can also be reliably detected.

Let $\mathrm{I}(s)$ be a vector with those indices of a cyclically shifted code word which are assigned to the same sub-packet s and let $i_o(s)$ with $o = 0,1,2 \ldots 23$ denote its element indices and o the element position in the vector. The elements of this vector shall be sorted in ascending order, i.e. $i_o(s) < i_1(s) < \ldots < i_{23}(s)$. Then, the rule for mapping the bits to position $m \in \{0,1,2,\ldots,35\}$ within sub-packet s is given by

$$\boxed{m = \begin{cases} 11 - \left\lfloor \frac{o}{2} \right\rfloor & \text{for } o + s \text{ even} \\ 24 + \left\lfloor \frac{o}{2} \right\rfloor & \text{for } o + s \text{ odd} \end{cases}} \qquad (4)$$

Where $\lfloor x \rfloor$ is the largest integer less than or equal to x.

This rule holds for all bits (not only for the first 288 bits). For the first 288 bits the relation between i and o can be compactly formulated as

$$\boxed{o = \left\lfloor \frac{i}{24} \right\rfloor \text{ for } i < 288} \qquad (5)$$

If the code word has exactly the length 576, i.e. all bits fit into the core frame, the relation (5) holds also for all other bits. But for larger code words the relation between i and o becomes different and cannot be compactly formulated any more.

Let us now come back to the first interleaving step, i.e. the mapping to sub-packets for $i \geq 288$. When a code word consists of 576 bits only, the second half of a cyclically shifted code word is also distributed equally among the sub-packets of a core frame, but with a different order than the first half. Starting with $i = 288$, 12 bits ($i = 288,289,\ldots 299$) are mapped into the sub-packets with even indices s and the next 12 bits ($i = 300,301,\ldots 311$)

are mapped into the sub-packets with odd indices s. Subsequent blocks of 24 bits follow this mapping rule correspondingly.

For a core-frame-only transmission, the mapping scheme can be compactly formulated as

$$\boxed{s(i) = 2i \bmod S + \left\lfloor \frac{i}{S/2} \right\rfloor \bmod 2 \text{ for } i \geq 288 \text{ and } S = 24.} \quad (6)$$

The mapping scheme of this interleaver is illustrated in Figure 16. The code word at the top is subdivided into 12 segments of 48 bits. Each segment has its individual color. Red is the color for the 1st segment. These bits are mapped to the positions next to the pilot sequence. Ocher brown indicates bits of the 2nd segment. These are mapped to the next but one positions to the pilot sequence, and so on. Bit positions with the same color have the same distance to the pilot sequence. As can easily be seen, the sub-packets are filled starting with positions close to the pilot sequence (red) and ending at the sub-packet border (dark blue). The light yellow rectangle marks the region where the first 288 bits of a core frame are positioned in the sub-packets. The mapping scheme in this area does not change when an extension frame follows.

If the MPDU contains more than 20 bytes ($PSI > 20$), a core frame plus an extension frame is transmitted. According to Figure 12 the physical layer frame contains $26 + 8 \times PSI$ bits. A code word after convolutional encoding contains $3 \times (26 + 6 + 8 \times PSI) = 24 \times (PSI + 4)$ bits.

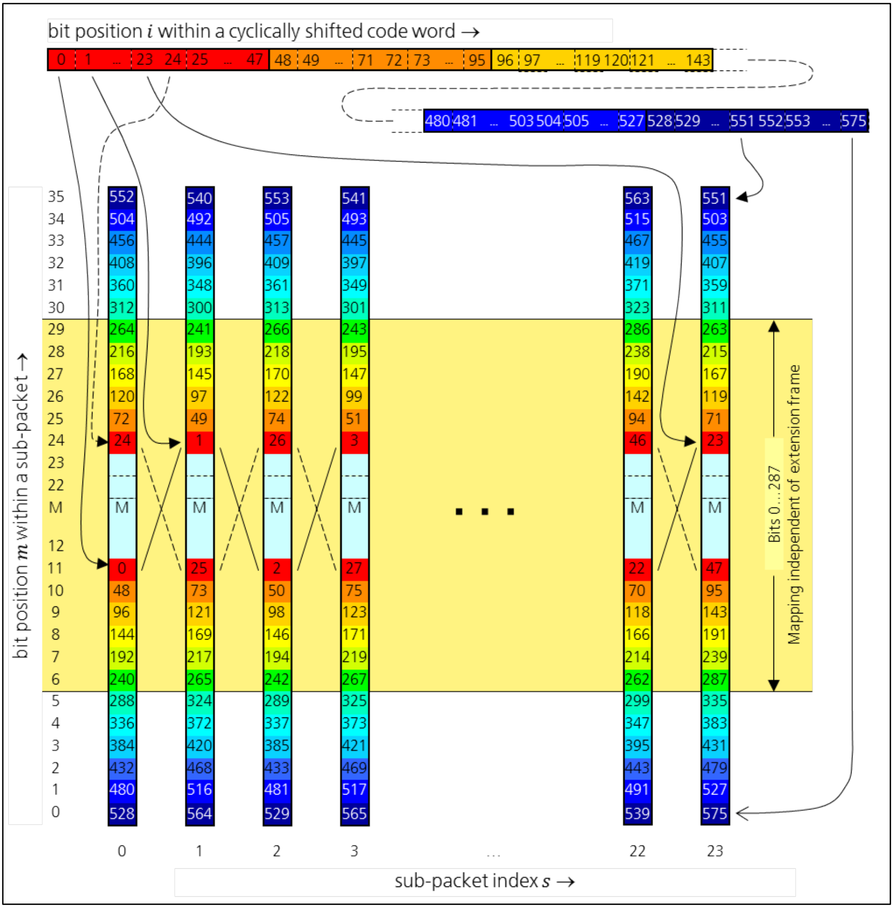


Figure 16: Interleaving scheme for core-frame-only transmission

Since each sub-packet carries 24 coded bits, each additional payload byte fills another sub-packet, i.e. the total number S of transmitted sub-packets and the number S_E of sub-packets in the extension frame are given by

$$\boxed{S = PSI + 4} \qquad (7)$$

and

$$\boxed{S_{\mathrm{E}} = PSI - 20} \qquad (8)$$

respectively.

The first 24 sub-packets form the core frame, the additional S_{E} sub-packets form the extension frame. This extension frame is, however, not simply filled with bits which do not fit into the core frame. This could result in a major performance loss of the bits in the extension frame.

Starting from the 289th bit ($i = 288$), the interleaver depends on the actual code word length. To achieve an almost equal distribution over the available sub-packets, the remaining bit sequence is segmented in groups of equal number G of bits given by

$$\boxed{G = S_{\mathrm{E}} + S_{\mathrm{C}}/2} \tag{9}$$

where $S_{\mathrm{c}} = 24$ denotes the number of sub-packets of the core frame. This is illustrated in Figure 17. There are always 24 of such groups, irrespective of the PSI value.

The first 12 bits of each group are placed into every other sub-packet of the core frame. The first 12 bits of the 1st group are placed into the even indexed sub-packets, the first 12 bits of the 2nd group are placed into the odd indexed sub-packets. For the 3rd group the even indexed sub-packets are used again and so on. The remaining bits of each group are mapped to the sub-packets of the extension frame in ascending order.

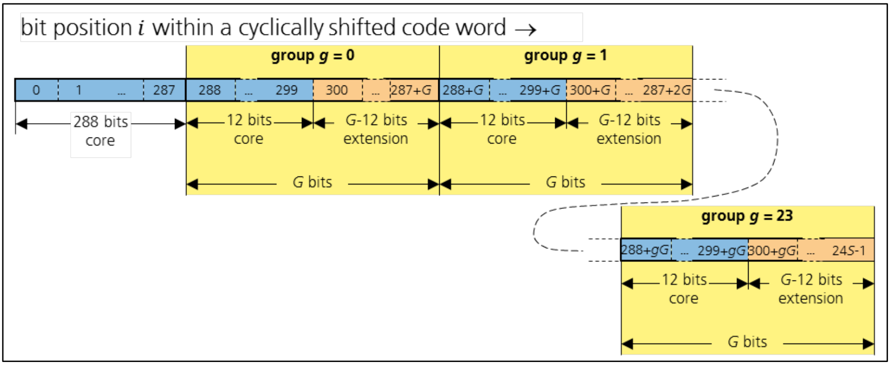


Figure 17: Assignments of bits from a cyclically shifted code word to core frame and extension frame

4.2.4 Pilot Insertion

The insertion of the pilot sequence is straight forward: The bit positions $m = 12, 13, \ldots, 23$ in each sub-packet are filled with the pilot sequence pattern resulting in a structure as shown in Figure 8. For the sub-packets of the core frame (i.e. the first 24 sub-packets of a telegram) the binary pilot pattern is 011101000010. For sub-packets of the extension frame the pilot pattern 010011111010 is used, starting from the left-most bit. I.e. the left-most bit is mapped to bit position $m = 12$.

Using different pilot sequences for core frame and extension frame prevents the receiver from accidentally mixing up radio bursts of an extension frame with those of a core frame.

At the receiving end, these sequences are used for signal detection as well as for estimation of frequency and timing offset, once a core frame is detected. Both estimates are required for subsequent demodulation of the data symbols. The detection and time estimation performance is mainly determined by the autocorrelation function (ACF) of the modulated wave form generated from a pilot sequence. For the two pilot sequences the magnitudes of these ACFs are shown in Figure 18. The false detection performance is determined by the cross-correlation function (CCF) of their modulated wave forms. This is shown in Figure 19.

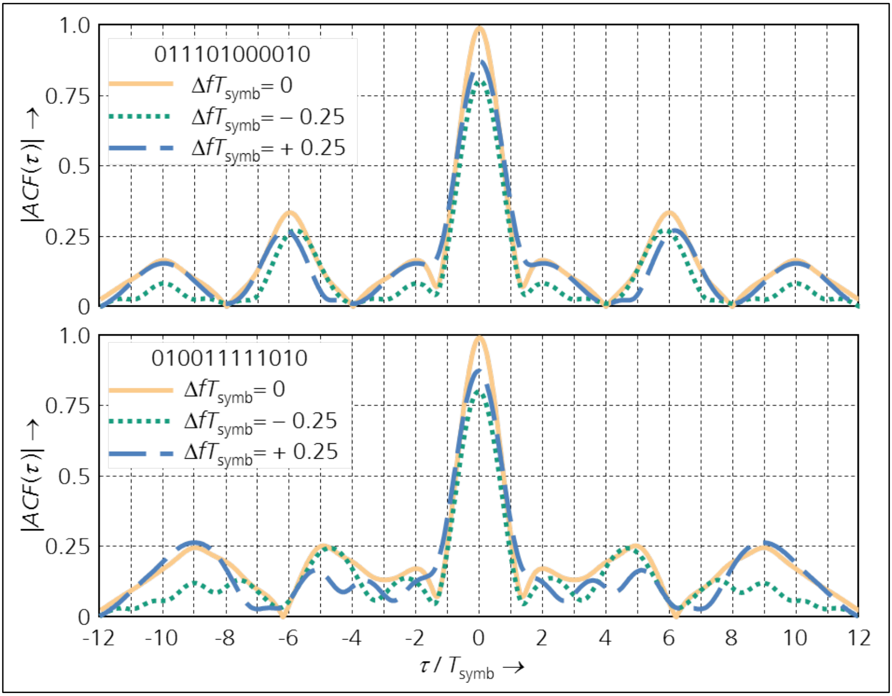


Figure 18: Autocorrelation functions of the modulated wave forms created from the pilot sequences used for core frame and extension frame; Parameter: frequency offset

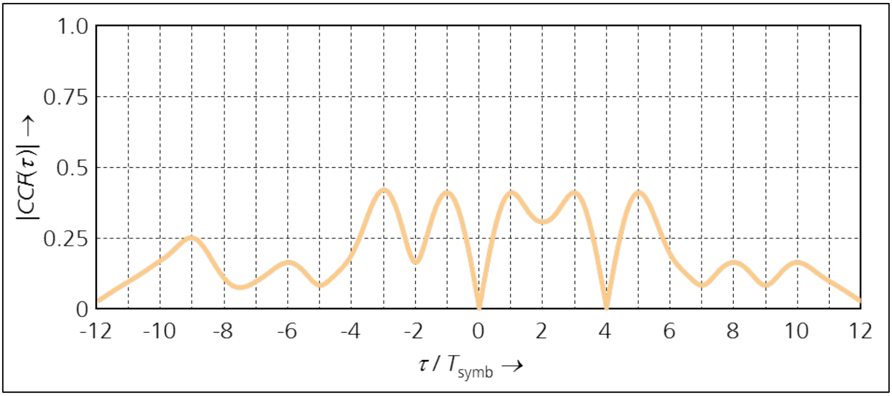


Figure 19: Cross-correlation function of the modulated wave forms of both pilot sequences

The ACFs and the CCF have the following main characteristics:

- The main lobe of both ACFs is very narrow, which enables an accurate estimation of the optimal sampling time phase in the receiver.
- The magnitude of the ACF side lobes is less than 0.3 corresponding to a peak to side lobe ratio of more than 10 dB. Hence, misdetections at wrong time instants are prevented almost perfectly.
- The ACFs are robust against carrier frequency offsets. In a matched filter receiver a frequency offset of a quarter of the symbol rate or less degrades the magnitude of the main lobe by less than 2 dB. This robustness allows coarse frequency spacing during the detection process in the receiver without loosing too much in detection performance.
- The magnitude of the CCF is low enough to prevent the receiver accidently assigning a sub-packet to a core frame although it belongs to an extension frame and vice versa.

4.2.5 Modulation

Each sub-packet with 36 bits is finally mapped to a time-continuous signal by a modulator. The TS-UNB profile uses either MSK (Minimum Shift Keying) or GMSK (Gaussian filtered Minimum Shift Keying) with $BT = 1$, both with differential precoding. MSK and GMSK are continuous phase frequency modulation formats with a fixed modulation index of $h = 0.5$.

Conceptually, the mapping can be subdivided into four processing steps as shown Figure 20. Let $e_{m,s}$ denote the bit at position m in sub-packet s.

1. The binary sequence of the bits $e_{m,s}$ in sub-packet s is first differentially precoded by combining two consecutive bits with an exclusive-or gate, i.e.

$$\boxed{d_{m,s} = e_{m-1,s} \oplus e_{m,s} \text{ for } m = 0,1,2,\dots} \qquad (10)$$

where by definition $e_{-1,s} = 0$ for all s.

2. From this sequence a time-continuous baseband signal is created by mapping each bit to a rectangular pulse whose width is equal to the symbol interval T_{symb} and whose amplitude carries the binary information: A binary 0 corresponds to the amplitude $+1$ and a binary 1 corresponds to the amplitude -1. This kind of signal is commonly referred to a NRZ-signal (Non-Return-to-Zero).
3. In case of GMSK the sharp jumps in the NRZ-signal are smoothed by passing this signal through a low-pass filter. Its transfer function has a Gaussian shape centered at zero. (This is where the name comes from: Gaussian filtered MSK). The only parameter which characterizes this filter is its 3dB-bandwidth B. This is commonly normalized to the symbol rate $1/T_{\text{symb}}$ and for short referred to as BT-parameter. For MSK this filtering step is skipped, i.e. $BT = \infty$.
4. Finally, the frequency modulator creates the transmit signal $s(t)$, whose instantaneous frequency is proportional to the (filtered) NRZ-signal. For Minimum Shift Keying (MSK) the modulation index is fixed to 0.5, i.e. the NRZ-amplitude 1 corresponds to a frequency offset of a quarter of the symbol rate.

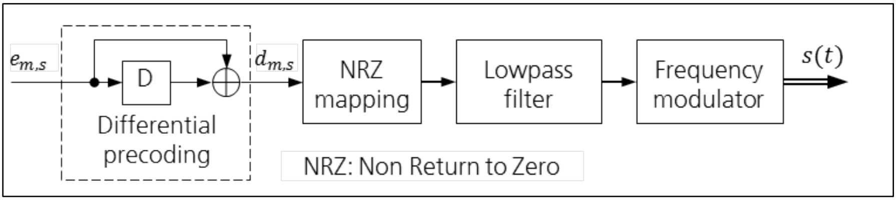


Figure 20: Differentially precoded GMSK

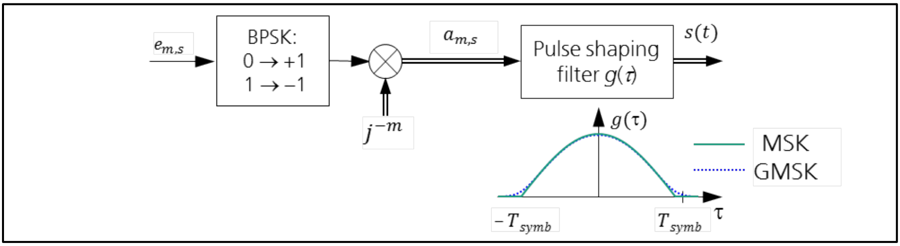


Figure 21: Representation of differentially precoded MSK as -π/2-rotated BPSK

In combination with differential precoding MSK can also be represented as a linear modulation scheme. It is in fact equivalent to $-\pi/2$-rotated BPSK (Binary Phase Shift Keying) with a pulse shaping filter as shown in Figure 21. In this model, the binary sequence $e_{0,s}, e_{1,s}, e_{2,s}, \ldots$ is first mapped to a sequence of data symbols from the BPSK symbol set $\{+1, -1\}$. These symbols are rotated by$-\pi/2$ per modulation interval (corresponding to a multiplication with j^{-m}, where m is the bit index within a sub-packet) and then passed through a filter, whose impulse response is a half cosine wave over two symbol intervals. For MSK the output signal $s(t)$ is exactly equivalent to that in Figure 20. The Gaussian filtered variant of MSK cannot be represented exactly in this way, but is well approximated, if the pulse shape of the filter is designed appropriately.
This linear representation of MSK and approximation of GMSK is an interesting model for designing a coherent demodulator. The demodulator reduces in fact to a BPSK-detector when the T_{symb}-spaced samples are derotated by $\pi/2$ per sample prior to detection. Only the phase at some point of the received radio burst must be known. For the center of a radio burst the phase can easily be estimated from the pilot sequence of a radio burst with sufficient accuracy.

Figure 22 shows the mapping from sub-packet bits to rotated BPSK-symbols for the first four bits of a sub-packet in equivalent complex baseband representation. For subsequent bits, the mapping pattern repeats periodically. This symbol sequence describes exactly the input to the pulse shaping filter of the linear model of Figure 21. For MSK the phase transitions from one symbol to the next can be mathematically described by complex exponential functions with the baseband frequency $\Delta f \; = \; \pm 0.25 r_S$ where r_S is symbol rate on the radio link and the sign represents the binary information.

For the ultra-low power (ULP) mode of the TS-UNB specification, this rate is fixed to

$$\boxed{r_{\text{symb}} = \frac{1}{T_{\text{symb}}} = 3 \; \times 26 \times 10^{6} \times 2^{-15} = 2380.371 \text{ symbols per second}} \qquad (11)$$

For the extended range (ER) mode it is given by

$$r_{\text{symb}} = \frac{1}{T_{\text{symb}}} = 26 \times 10^6 \times 2^{-16} = 396.729 \text{ symbols per second} \tag{12}$$

Both can be easily derived from a 26 MHz clock.

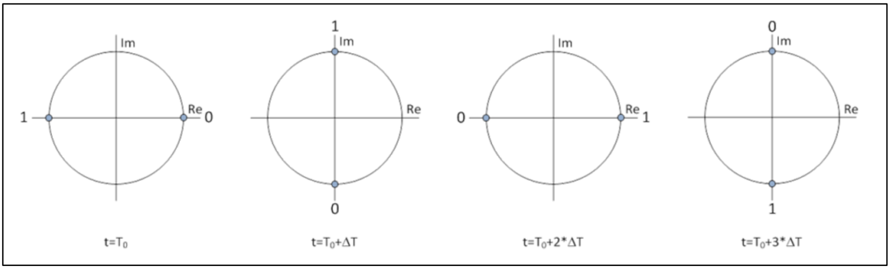


Figure 22: Mapping of bits $e_{m,s}$ to modulation symbols $a_{m,s}$ for MSK and GMSK

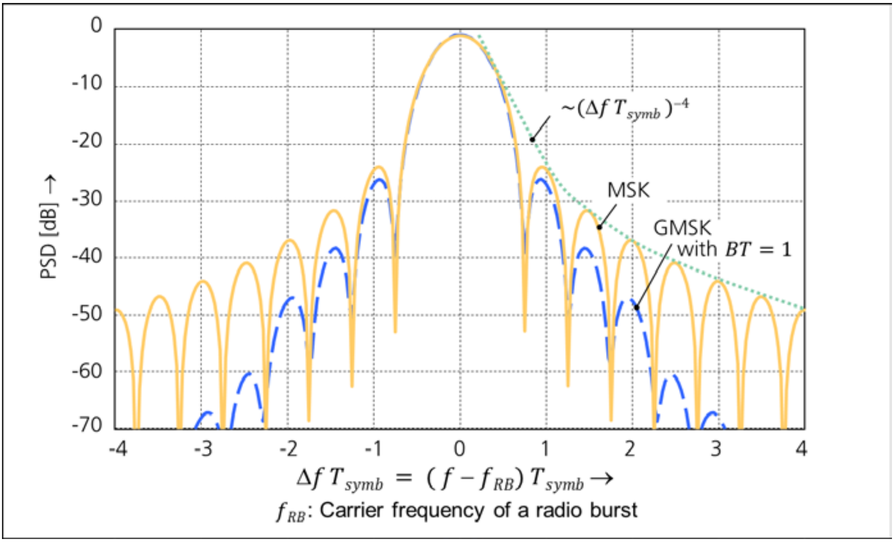


Figure 23: Power spectral density (PSD) of MSK and GMSK with $BT = 1$

Figure 23 shows the power spectrum of both modulation formats. The frequency axis is normalized to the center frequency f_{RB} of a radio burst and to the symbol rate r_{symb}. In this normalization the integer numbers at the horizontal axis corresponds to carrier index shifts. While the MSK power spectrum decays proportional to $1/\Delta f^4$ (in the dB-scale: $-40\lg\Delta f$) the GMSK-spectrum decays much faster. This is the main advantage of GMSK: The adjacent channel interference is reduced drastically, by more than 10 dB at a frequency offset of 2 times the symbol rate. But the effect on the modulation pulse is negligible as shown in Figure 21. From a receiver perspective, for both modulation formats the same demodulator can be used - without any difference.

A main characteristic of MSK- and GMSK-modulated signals is its constant envelope, i.e. efficient class-C power amplifiers can be used in the transmitter. The differential precoding makes the signal suited for coherent detection, giving a realistic gain of about 2.5 dB over non-coherent detection with respect to the required signal-to-noise ratio at the receiver.

4.3 Uplink Time-Frequency-Patterns

As a final step in the signal-processing chain, the modulated sub-packets are up-converted to carrier frequencies, each sub-packet to its own frequency, and transmitted at well-defined time instants according to the assigned time-frequency pattern.

In order to increase the degree of randomness, a quasi-random carrier frequency offset C_{RF} is introduced which is calculated anew before each new radio frame. This offset must of course be derived from data which is available at both sides: the base station and the end device. For this purpose, the payload-CRC is used. The least significant bit (right-most bit in the payload-CRC-field in Figure 12) selects either the upper channel (0) or the lower channel (1) for transmission. If only one channel is available, this bit has no meaning. The remaining 7 bits are interpreted as integer value ranging from 0 to 127. Let v_{co} denote this value. In order to keep the RF-signal within the nominal frequency band, the range of this carrier offset is limited depending on the maximal tolerance of the local oscillator used in the end device. In its current version, the TS-UNB specification distinguishes two classes of local oscillators:

- for a frequency tolerance less than or equal to ±10 ppm, the number of offset values is limited to $n_{\mathrm{co}} = 11$

- for a frequency tolerance greater than ±10 ppm but not greater than ±20 ppm, the number of offset values is limited to $n_{\mathrm{co}} = 3$

The carrier offset in integer multiples of the channel spacing is determined by

$$\boxed{C_{\mathrm{RF}} = v_{\mathrm{co}} \operatorname{mod} n_{\mathrm{co}} - \lfloor \frac{n_{\mathrm{co}}}{2} \rfloor.} \tag{13}$$

For $n_{\mathrm{co}} = 3$, C_{RF} can take on one of only 3 values: -1, 0, +1. For $n_{\mathrm{co}} = 11$ C_{RF} ranges from -5 to +5. C_{RF} multiplied with the channel spacing gives the nominal frequency offset in Hz which is applied for all radio bursts of the current radio frame (core frame and extension frame).

4.3.1 Time-Frequency Patterns for the Core Frame

For the core frame two groups with 8 fixed time-frequency patterns, each are specified for the standard operation and an additional pattern, is defined for time-critical applications. All patterns are defined in form of tables in the TS-UNB specification. The main properties of these patterns have already been mentioned in section 3.1.1. An end device uses the patterns of a pre-defined group in a well-defined order. Patterns from the first group are used, if the telegrams are only transmitted once. If retransmission is applied, the patterns from the 2nd group are used for both, initial transmission and repetition.

4.3.2 Time-Frequency Patterns for the Extension Frame

The time-frequency pattern of the extension frame is generated from the payload header information, specifically from the 16 bits comprising the two CRC-fields in Figure 12. On the basis of these 16 bits a quasi-random sequence with 16-bit integer values is generated, one value per radio burst, from which the time-frequency pattern can be calculated.

For generating the quasi-random sequence, a linear feedback shift register (LFSR) of length 16 with feedback polynomial 0xB4F3 (in hexadecimal notation, the first bit corresponds to the MSB) according to Figure 24 is used. The two CRC-fields from the header serve as seed, i.e. they define the initial state of the LFSR. In order to avoid an all-zero sequence (the 16 CRC-bits may in fact all be zero), the MSB of the register is initially always set to one.

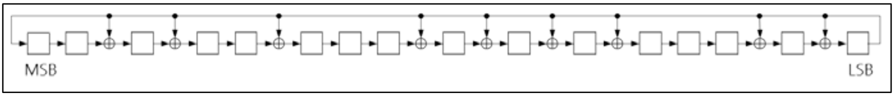


Figure 24: Linear feedback shift register for generating a pseudo-random sequence of 16-bit integer values

Let $R[s_\mathrm{e}]$ denote the register state for the s_e^th radio burst of the extension frame with $s_\mathrm{e} = 1,2,3,\dots,$ where $R(1)$ is defined by the 16 CRC-bits from the payload header. Then, the time interval between the centers of radio bursts s_e and $s_\mathrm{e} - 1$ in number of modulation symbol intervals is defined by

$$\boxed{T_\mathrm{RB}(s_\mathrm{e}) = T_0 + R(s_\mathrm{e}) \bmod 128} \qquad (14)$$

where T_0 depends on the pattern group used for the core frame and is determined by

$$\boxed{T_0 = \begin{cases} 337 & \text{if pattern group 1 or 2 is used} \\ 66 & \text{if pattern group 3 is used} \end{cases}} \qquad (15)$$

The index of the carrier frequency for the s_e^th sub-packet can be calculated from

$$\boxed{C_\mathrm{RB}[S_\mathrm{e}] = \left\lfloor \frac{R[s_\mathrm{e}]}{256} \right\rfloor \bmod 25} \qquad (16)$$

It shall be emphasized that the carrier indices here range from 0 to 24, i.e. covering 25 carrier indices, while for the core frame they range only from 0 to 23.

4.4 Uplink Performance for the Static AWGN-Channel

In order to assess the basic transmission performance of the TS-UNB standard, the packet error rate PER for core frame transmissions over the static AWGN-channel has been estimated by link level simulations, including realistic MSK-modulation, coherent detection and soft decision decoding with the Viterbi-algorithm. To assess the robustness against interferences, the simulations are repeated with a fixed number of erased radio bursts per frame. The erasure pattern changes randomly from frame to frame. A radio burst is called erased, if it is marked as unreliable, because of severe interference. The data bits of erased bursts are not used at all by the channel decoder. Its soft decision values are set to 0.

Perfect receiver synchronization – for frequency, time and phase – is assumed. With realistic estimations of the synchronization parameters a loss in the order of 1 dB with respect to the E_b/N_0 must be taken into account. Figure 25 shows the results.

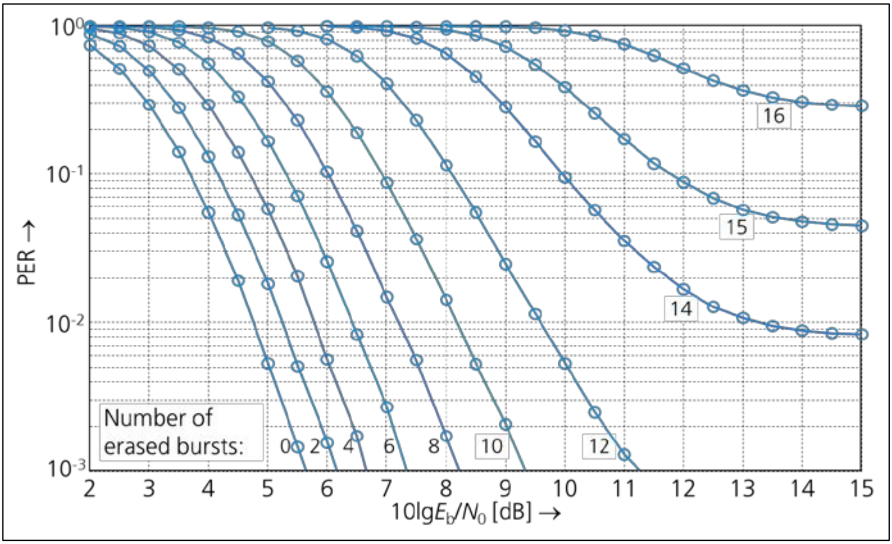


Figure 25: Packet error rate (PER) of TS-UNB transmission (core frame) over a static AWGN-channel with matched filter receiver, coherent detection, soft decision decoding and perfect receiver synchronization; parameter: Number of erased radio bursts; E_b: received energy per information bit

It should be mentioned that E_b refers to the received energy per information bit, i.e. per bit after the channel decoder. Since each information bit is represented by 3 coded bits, the energy per coded bit is only 1/3 of this value, corresponding to a shift of -4.8 dB. This offset must be taken into account when considering e.g. the signal-to-noise power ratio SNR at the matched filter output.

The curves of Figure 25 indicate already the impressive interference resilience of the TS-UNB standard. At the cost of a slight performance loss a telegram with a few erased radio bursts could be recovered with acceptable reliability. Even if 12 from 24 radio bursts are erased, an acceptable PER of 1…10 % could be achieved, if the E_b/N_0 is around 4.5 dB higher compared to reception without any erasures.

4.5 Retransmissions in the Uplink

For performance improvement a radio frame can optionally be retransmitted. If retransmission is applied, the TSMA-patterns from the 2nd group are used for both, the initial and the retransmitted radio frame. Both have also the same content and the same structure. The main difference is the time of transmission. For the repeated radio frame a well-defined time-offset with respect to the initial frame is used. For its calculation, the two least significant bits of the header-CRC from the uplink payload are used. Let v_{ts} denote the corresponding integer value ranging from 0 to 3. Let furthermore T_s denote the absolute time instant for the initial transmission of radio burst number s of the selected TSMA-pattern. Then, the time for transmitting the s^{th} radio burst in the repeated radio frame – normalized to the modulation symbol interval – is given by

$$\boxed{T'_S = T_s + 42(v_{ts} + 2).} \tag{17}$$

With 84 modulation symbol intervals the minimal time offset ($v_{ts} = 0$) is definitely larger than the duration of a radio burst which equals 36 symbol intervals only. The maximal time offset of 210 modulation symbol intervals ($v_{ts} = 3$) is less than the minimal transmission-free time between any two radio bursts of the radio frame, which is 300 modulation symbol intervals. Even for the maximal time offset of 210, both radio frames, the initial and the retransmitted one, overlap in time to a large extent such that there is only a marginal delay in receiving the retransmitted frame. This is another advantage of telegram splitting: Due to the short radio bursts, retransmission is feasible with almost no delay.

To obtain the time offset from data is another contribution to randomize the transmission of the radio bursts. If it happens by chance that there is a downlink collision of the 1st transmission, this quasi-random time offset reduces the probability that the same collision happens during the repetition.

The transmission reliability could be even more increased, if two channels with the same bandwidth are available, e.g. 2 x 100 kHz for the standard mode. In this case, both radio frames are transmitted in different bands.

4.6 Base Station Receiver Aspects

In order to allow for very cheap hardware of the end devices, the TS-UNB specification allows a tolerance of ± 20 ppm of the local oscillator w.r.t. the nominal carrier frequencies. At a carrier frequency around 900 MHz the frequency error can be up to 18 kHz, which is more than 7 times the symbol rate of a standard end device. This has to be taken into account by the detection algorithm at the base station.

Frequency offset estimations can be done on the basis of the pilot sequences. The estimate from a single pilot sequence with length of 12 bits would not be sufficient for a reliable coherent demodulation. But all radio bursts of the same end device have almost the same frequency offset. This priori knowledge can be taken into account in the detection process and for frequency offset estimation. In fact, applying a joint detection and frequency estimation it is possible to detect a telegram using TSMA with a high reliability, even if the signal-to-noise ratio is below 0 dB.

For estimating the optimal sampling time instants for the symbol decisions also an estimation algorithm can be applied which takes all potential radio burst into account. The maximal time deviation due to 20 ppm frequency tolerance of the local oscillator is less than 17% of a modulation symbol interval during the transmission time of a core frame.

5 TS-UNB Downlink Description

5.1 Overview

In the downlink a telegram is only transmitted after the reception of an uplink telegram. The downlink transmission is initiated by a flag in the MAC-header of the previous uplink message. Hence every downlink transmission needs to be preceded by an uplink transmission of an end device. After sending an uplink telegram to the base station, the end device may open a downlink window for the reception of a downlink telegram from the base station. The transmission starts after a predefined time of $2^{14} = 16{,}384$ symbol intervals after reception of the uplink telegram. To be precise, this time is measured from the center of the last received radio-burst of the last transmitted radio frame in the uplink to the center of the first radio-burst of the downlink transmission. Since the transmission delay in an ultra-narrowband system is always only a small fraction of a symbol interval, it does not need to be taken into account for the bidirectional communication, i.e. the receive time at the base station can be set almost equal to the transmit time of the end device.

As in the uplink, also the downlink message on the radio path is subdivided into a core frame and an extension frame. The core frame is used only as authenticated wakeup and acknowledgment of the previous uplink transmission. Telegram splitting is applied and the message which is to be transmitted within the core frame is split over 9 sub-packets and may (but must not be) repeated once. The total window for the core frame covers always 18 radio bursts, also if the frame is not repeated. The base station can decide (e.g. upon the field strength of the uplink receive signal) whether it repeats the downlink transmission or not.

Every downlink transmission starts with a core frame and may be followed by an optional extension frame. The extension frame itself is subdivided into maximal 11 blocks on the radio path, each comprising 18 radio bursts. The number of blocks is defined by the amount of user data. Whenever an extension frame is transmitted it consists of at least one block. The time between the core frame and the start of the first block of the extension frame can be selected by the base station. Its value is transmitted in the core frame such that the end device has this knowledge after it has decoded the core frame successfully. If the extension frame consists of more than one block, an idle time between their transmissions is introduced.

Figure 26 gives an overview of the complete downlink scheduling with an extension frame containing several blocks. The range of the indicated time intervals is given in Table 5.

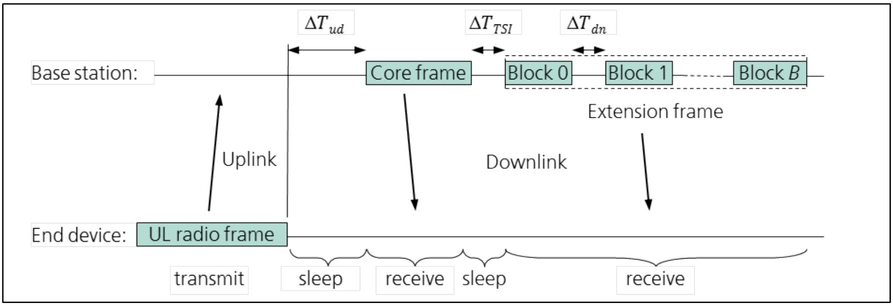


Figure 26: Uplink/downlink scheduling

Parameter	Range of values	Default Value	Description
ΔT_{ud}	Fixed	16,384 ±2 symbols	Time interval between uplink and downlink transmission
ΔT_{dn}	512 or 7168	512	Time interval between blocks of extension frame
ΔT_{TSI}	84 … 65,532	384	Time interval between core frame and extension frame

Table 5: Time intervals of uplink/downlink time scheduling; the time values in the first 3 rows are given in number of modulation symbol intervals

The signal processing chain from a physical layer data packet to the RF-signal in the downlink is similar as in the uplink. For completeness, it is shown in Figure 27 again.

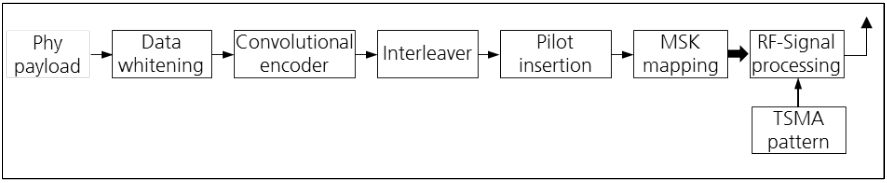


Figure 27: Block diagram of the wave form generation in the downlink

There is one essential difference to the uplink: While in the uplink the data of the complete telegram (core frame and extension frame) are encoded at once to give a single code word, this is done separately for the core frame data and for each block of the extension frame data. The message for the core frame gives a code word and the message for the extension frame is split into 4 blocks and each block gives another code word.

But aside of this difference, the principles for data whitening, encoding and modulation are the same as in the uplink. Also the carrier frequency offset as described in section 4.3 is applied to all radio bursts of the downlink radio frame. Therefore the description of these steps does not need to be repeated here. Only the interleaver, pilot insertion and the TSMA-pattern generation are quite different. Since these are also different for core frames and extension frames, they are described in separate sections.

5.2 Downlink Core Frame

5.2.1 Physical Layer Data Structure of the Core Frame

A data packet on the physical layer of the TS-UNB downlink for the core frame does not contain any data from the MAC-layer. The purposes of the core frame are the following:

- to acknowledge the last uplink transmission of the end device,
- to inform the end device whether an extension frame follows or not,
- if an extension frame follows, to inform the end device about the length and the time offset between the last uplink core frame and the downlink extension frame and

- optionally it can provide a ciphered authentication message.

The data packet for the downlink core frame has a structure as shown in Figure 28.

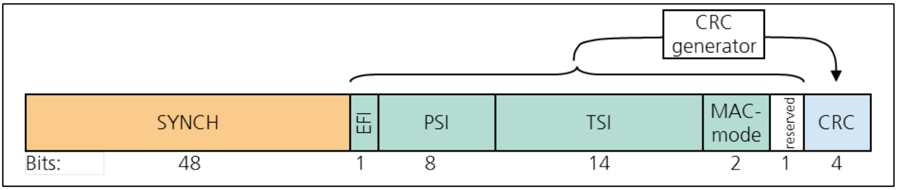


Figure 28: Payload structure for the downlink core frame on the physical layer

SYNCH-field

The main purpose of the SYNCH-field is synchronization. As will be explained later, the 144 coded bits of the SYNCH-field are mapped to the pilot fields of the first 9 consecutive sub-packets of the downlink core frame. As such it is not a typical data field, since there is no new information contained in the SYNCH-field. The data must be known to the end device before the base station transmits the first radio burst of the core frame.

The content of the SYNCH-field depends on the MAC-mode. If a variable MAC-mode is used it is simply filled with the 4-fold periodic repetition of the bit pattern 0100001011101000 which is the concatenation of the two 8 bit long pilot sequences defined for the sub-packets of the extension frame.

If the fixed MAC-mode is used, it is filled with a bit pattern derived from the 64-bit long Extended Unique Identifier code (EUI64) of the specific end device. This code is the successor of the well-known Ethernet address and is a worldwide unique identifier of a communication device. The EUI64-code together with some counters known at the intended end device is cryptographically processed. Since the counters change from message to message, they cause completely other bit pattern after encryption. The leading 48 bits of the ciphered block fill the SYNCH-field. Only the intended end device is able to synchronize to the core frame. Hence, the SYNCH-field serves also as an encrypted sign and authentication verifier.

EFI-field

The first green field is the Extension Frame Indicator (EFI). It consists of one bit (0/1) only and indicates whether an extension frame follows (1) or not (0).

PSI-field

The next field contains the Packet Size Indicator (PSI). It is 8 bits long and contains the length of the MPDU which is going to be transmitted in the extension frame that follows. As in the uplink, the length of the MPDU is provided in number of bytes. It ranges from 0 to 255.

TSI-field

It follows the 14 bit long Transmission Start time Indicator (TSI). The integer value represented by the 14 bits times 4 gives the time offset ΔT_{TSI} between core frame and extension frame in number of modulation symbol intervals:

$$\boxed{\Delta T_{TSI} = 4\,TSI} \tag{18}$$

On the basis of this value the end device knows when to open it’s receive window.

MAC-mode

The last green field indicates the used MAC-mode and has the same meaning as in the uplink as described in section 4.1. In fact, this field contains exactly the two bits from the uplink telegram. It is important that in the downlink the same MAC-mode is used as in the uplink. Only then the end device knows how to interpret the content of the SYNCH-field.

Reserved field

The reserved field contains one bit which may be used in future releases. Actually it has no meaning and is always set to 0.

CRC-field

Finally, 4 cyclic redundancy check bits are calculated from the sequence of EFI, PSI, TSI, MAC-mode and the reserved bit. These CRC-bits are appended at the end of the packet. The 4 CRC-bits are generated by a linear feedback shift register (LFSR) as shown in Figure 29. Initially, the register cells are filled with ones. It works in the same way as described for Figure 13, but with only 4 register cells (instead of 8) and another generator polynomial.

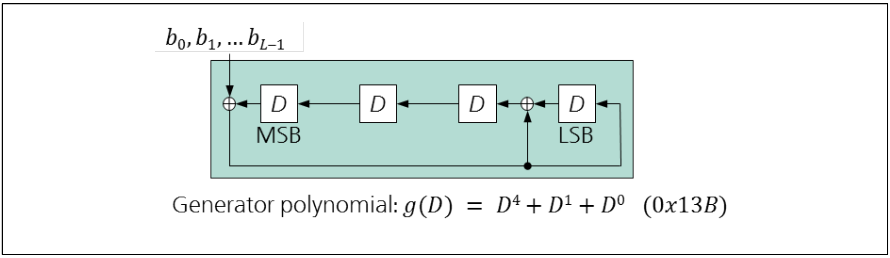


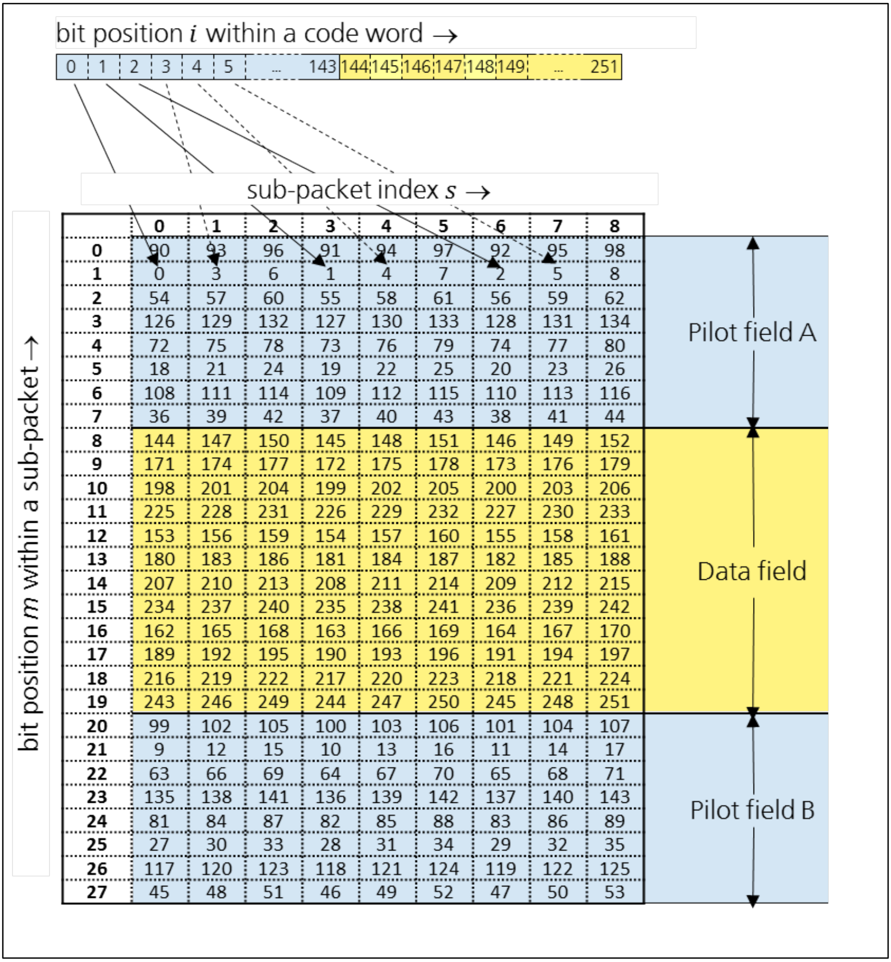
Figure 29: CRC-generator for 4 check bits according to the TS-UNB standard (Hint: In the ETSI-document the leading 1 in the hexadecimal representation of the generator polynomial is omitted.)

5.2.2 Signal Processing of the Physical Layer Payload for the Downlink Core Frame

The data packet with 78 bits is first whitened as described for the uplink in section 4.2.1. Then, 6 zero bits are appended (tail bits) and the whole packet is encoded by a 1/3-rate convolutional code with constraint length 7 as described in section 4.2.2, giving a code word of length 252 bits.

Interleaving and pilot insertion

The 252 coded bits are interleaved such that they are equally distributed over 9 sub-packets, each carrying 28 coded bits. The mapping scheme is provided as a single table in the specification. It is shown in Figure 30.



	0	1	2	3	4	5	6	7	8
0	90	93	96	91	94	97	92	95	98
1	0	3	6	1	4	7	2	5	8
2	54	57	60	55	58	61	56	59	62
3	126	129	132	127	130	133	128	131	134
4	72	75	78	73	76	79	74	77	80
5	18	21	24	19	22	25	20	23	26
6	108	111	114	109	112	115	110	113	116
7	36	39	42	37	40	43	38	41	44
8	144	147	150	145	148	151	146	149	152
9	171	174	177	172	175	178	173	176	179
10	198	201	204	199	202	205	200	203	206
11	225	228	231	226	229	232	227	230	233
12	153	156	159	154	157	160	155	158	161
13	180	183	186	181	184	187	182	185	188
14	207	210	213	208	211	214	209	212	215
15	234	237	240	235	238	241	236	239	242
16	162	165	168	163	166	169	164	167	170
17	189	192	195	190	193	196	191	194	197
18	216	219	222	217	220	223	218	221	224
19	243	246	249	244	247	250	245	248	251
20	99	102	105	100	103	106	101	104	107
21	9	12	15	10	13	16	11	14	17
22	63	66	69	64	67	70	65	68	71
23	135	138	141	136	139	142	137	140	143
24	81	84	87	82	85	88	83	86	89
25	27	30	33	28	31	34	29	32	35
26	117	120	123	118	121	124	119	122	125
27	45	48	51	46	49	52	47	50	53

Figure 30: Interleaving scheme for the downlink core frame

A major property of the mapping scheme is that the first 144 bits of a code word are mapped to the pilot fields of the 9 sub-packets as indicated in Figure 30. At first glance the sub-packets seem to have no pilot sequences at all. A closer look reveals, however, that the first 144 bits of a code word depend only on the SYNCH-field of the message in Figure 28, whose content is exactly known to the receiver. So the bit patterns in the two pilot fields are completely known to the end device prior to reception of the core frame in the downlink. Hence they can be used as pilot sequences.

Downlink time-frequency-patterns for the core frame

For the core frame 8 fixed time-frequency patterns with 18 radio bursts are specified. All patterns are defined in form of tables in the TS-UNB specification. One of these must be selected for a specific downlink transmission. This selection is based on the most significant four bits from the header-CRC of the previous uplink message. These are the right-most bits of the header-CRC-field in Figure 12. The right-most bit from these four is ignored, and the remaining 3 bits are interpreted as integer value ranging from 0 to 7. Since the pattern indices in the specification tables ranges from 1 to 8, this value has to be incremented by 1 to give the pattern index as it is defined in the specification.

Once the pattern is selected, the first 9 radio bursts are used for a single transmission of the core frame payload.

Another important step in the downlink is the adaptation of the carrier frequencies to the true frequencies used by the end device. The base station obtains the frequency deviation between the local oscillators of the base station and of the end device by analyzing the pilot sequences of the radio bursts of the previous uplink radio frame. This deviation is applied to the radio bursts of the downlink radio frame such that the receiver of the end device does not need to search in a large frequency band. In a static radio environment the end device could in fact omit the frequency correction at all. This is, however, not recommended, because in dynamically changing radio environments the uplink frequency estimate could be biased due to one-sided Doppler shifts. The implementation effort for frequency correction is anyway negligible.

5.2.3 Retransmissions of the Core Frame Message

Optionally, the downlink message for the core frame can be retransmitted once within the same radio frame. Based on the actual receive quality of the previous uplink message the base station can decide to retransmit the message in order to increase the reception reliability at the end device. If it is retransmitted, it has exactly the same content as the first. However, its time-frequency pattern is different: It uses the second half of the TSMA-pattern selected for the first transmission, where the same frequency offset has to be applied as for the initial transmission.

5.3 Downlink Extension Frame

5.3.1 Block Slicing

The downlink extension frame is subdivided into blocks with 18 radio bursts each. They carry the data from the MAC-layer provided in the MAC packet data unit (MPDU). The MPDU may have a size between 1 and 250 bytes. If the MPDU size is 24 bytes or less, it is transmitted in a single block. If the size exceeds 24 bytes, the MPDU is sliced into a number of B blocks, with

$$\boxed{B = \left\lceil \frac{P}{24} \right\rceil} \qquad (19)$$

where $P \in \{1,2,3,\dots,250\}$ is the size of the MPDU in bytes and $\lceil x \rceil$ means rounding x towards the nearest integer value equal to or larger than x.

If P is divisible by B, the bytes are equally distributed over the blocks. If P is not divisible by B, the first block(s) contain one more byte than the subsequent block(s). Example: Let the MPDU size be $P = 49$. According to (19) the number of blocks is $B = 3$. Since $49 = 3 \times 16 + 1$, the first block contains 17 bytes, the 2nd and the 3rd block contains 16 bytes each. The number of bytes in block b with $b \in \{1,2,\dots,B\}$ can be obtained from the general relation

$$\boxed{n_b = \left\lfloor \frac{P}{B} \right\rfloor + \left\{ \begin{array}{ll} 1 & for\ b \le P \bmod B \\ 0 & else \end{array} \right. ,} \qquad (20)$$

where B is obtained from (19) and $\lfloor x \rfloor$ means rounding x towards the nearest integer value equal to or smaller than x. To get a rough idea how n_b and B depend on P, the relations (19) and (20) are visualized in Figure 31.

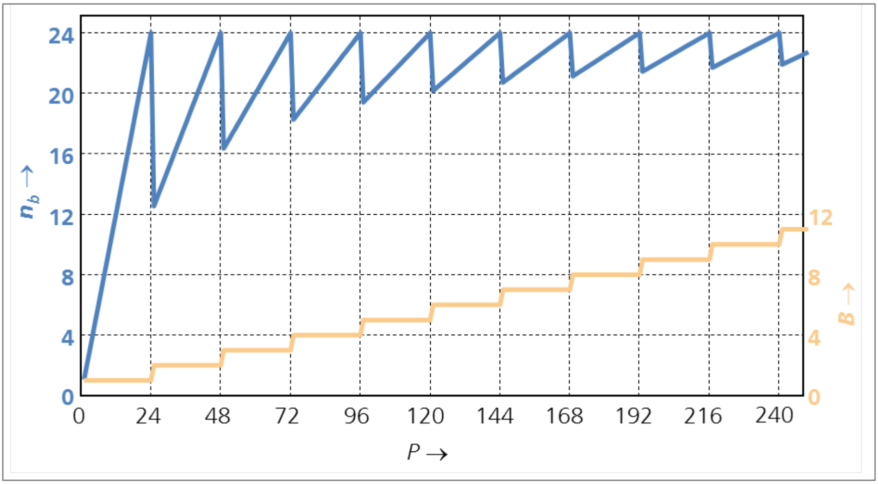


Figure 31: Number n_b of bytes per block (blue) and number *B* of blocks (orange) versus the MPDU size *P* in bytes

5.3.2 Physical Layer Payload Structure of a Block for the Extension Frame

All blocks have the same payload structure as illustrated in Figure 32.

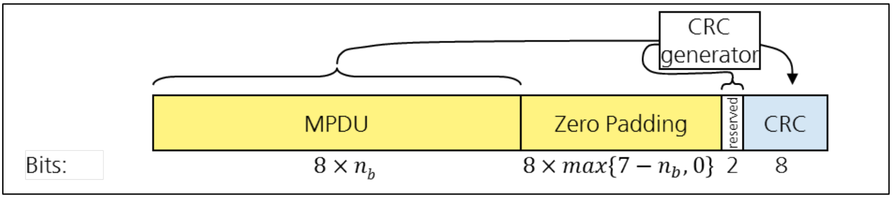


Figure 32: Physical layer payload structure of a block for the downlink extension frame; the number n_b of MPDU bytes for block b is determined by (20)

MPDU-field and zero padding

The yellow field is the core field. It is minimal 7 bytes long and it contains the MAC Packet Data Unit (MPDU) and padded zeros, if the MPDU is less than 7 bytes long. If the size of the MPDU is 7 bytes or more, it fills the yellow field completely without any additional zero bytes. If the MPDU contains more than 24 bytes, the MPDU is split into more blocks and the MPDU-field in Figure 32 contains only a part – namely n_b bytes – of the MPDU.

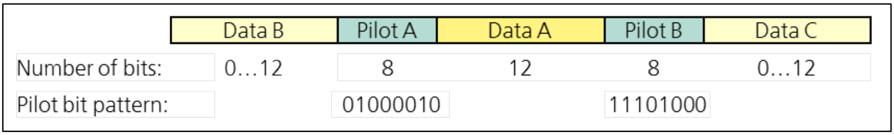
Reserved field

The reserved field consists of 2 bits which may be used in future applications. Actually they have no meaning and are always set to 0.

CRC-field

The CRC-field contains 8 cyclic redundancy check bits generated from the n_b bytes of the MPDU and the 2 reserved bits, excluding possibly padded zeros. The overall payload of the first block contains minimal 66 and at most 202 bits. If another block follows, the first block contains at least 336 bits.

The sub-packet structure used exclusively for the downlink extension frame is shown in Figure 33.



	Data B	Pilot A	Data A	Pilot B	Data C
Number of bits:	0…12	8	12	8	0…12
Pilot bit pattern:		01000010		11101000	

Figure 33: Sub-packet structure for the downlink extension frame

5.3.3 Signal Processing of the Physical Layer Payload of a Block for the Downlink Extension Frame

The payload with 66 … 202 bits is first whitened as described for the uplink in section 4.3.1. Then, 6 zero bits are appended (tail bits) and the whole block is encoded by a 1/3-rate convolutional code with constraint length 7 as described in section 4.3.2. The resulting code word has a length that ranges from 216 to 624 bits depending on the payload size.

Interleaving and pilot insertion

The interleaver provides the mapping from the bit positions i within a code word to the sub-packet indices s and the bit position m within a sub-packet. The mapping scheme is provided as a single table in the specification. Without going into details the principles behind the mapping scheme shall be mentioned:

- Any 18 consecutive bits from a code word are mapped to distinct sub-packets.
- The sub-packets are filled almost equal.
- The first 216 bits of a code word fill data field A in Figure 33, starting with the bit positions next to the pilot fields and ending at the positions in the middle of the data field.
- The remainder of the code word fills data fields B and C. The filling order follows also here the principle by starting with bit positions next to the pilot fields.

The filling process stops with the last bit from the code word. The data fields B and C are usually not completely filled. As a result, the lengths of the data fields B and C may differ by 1 bit and they may differ from sub-packet to sub-packet by 1 bit within a block of the extension frame.

The pilot fields A and B are filled with fixed pilot sequences, see Figure 33.

Downlink time-frequency-patterns for the extension frame

Any block of the downlink extension frame uses the same time-frequency pattern which was used by the previous downlink core frame.

5.3.4 Retransmission of the Extension Frame

In the actual TS-UNB specification no repetition for the downlink extension frame is foreseen.

6 Special Synchronization Bursts for Low-Cost Receivers

For easier synchronization in the receiver (e. g. for low complexity receivers) an optional synchronization radio-burst may be used before the core frame is transmitted.

6.1 Uplink Synchronization Burst

The synchronization burst in the uplink is transmitted prior to the core frame and shall help the receiver to simplify the search for the uplink core frame. It is very short and has in fact the same duration as a radio burst of a core frame, but its content is different. Whenever it is used, its carrier frequency is fixed and defined by the carrier frequency index 25. The nominal carrier frequency can be obtained from (1) with $C_{RB}(0) = 25$. Since this carrier frequency is not used by the core frame, it is much less loaded than other carriers, which helps to improve the transmission reliability.

The structure of the synch-burst is shown in Figure 34.

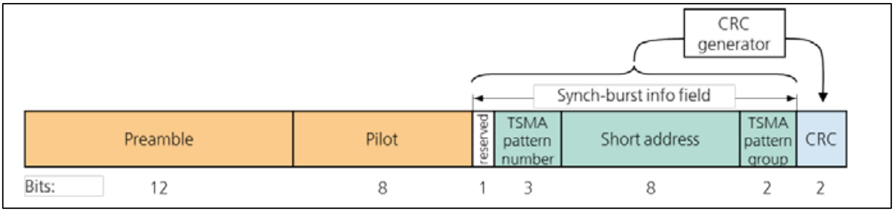


Figure 34: Uplink sync-burst data unit (SBDU)

Preamble field

The preamble field is 12 bit long and is filled with the fixed bit pattern 001100110011. In combination with differential precoding and MSK (see Figure 20) this pattern produces an RF-signal whose instantaneous frequency is constant within a symbol interval and alternating between symbols. It allows a simple algorithm to detect a synch-burst and to estimate the relative sampling phase (sampling time offset with respect to the internal symbol clock of the receiver). It allows also a coarse estimate of the end of the preamble. This is, however, not reliable enough. That is why an additional pilot field is appended.

Pilot field

The pilot field is 8 bit long and is filled with the fixed bit pattern 11010011. It serves essentially for a reliable estimate of the start time for the remaining fields.

Together with the preamble field it allows also a coarse estimation of the carrier frequency offset.

Reserved field

The reserved field is reserved for future use and is set to 0.

TSMA-pattern number

The uplink TSMA-pattern number indicates the time-frequency pattern used for the subsequent uplink transmission of the core frame. Since there are at most 8 patterns per group, all of them can be addressed by 3 bits.

Short address field

The short address field is 8 bits long and contains the least significant byte of the device's short address. This address is either a fixed address, e.g. the EUI64, if it is a device for unidirectional communication only, or a temporary non-unique address assigned during the attachment procedure, if the device is designed for bidirectional communication.

TSMA-pattern group

The uplink TSMA-pattern group indicates the group from which the time-frequency pattern indicated by the TSMA-pattern number is selected. The current specification contains three groups and the group index is given by the integer value obtained from the two bits of this field plus 1.

CRC-field

Finally, 2 cyclic redundancy check bits are calculated from the synch-burst information field indicated in Figure 34.

The uplink synch-burst is transmitted without any whitening, channel encoding and interleaving. The modulation, however, is the same as used in the subsequent core frame: Either MSK of GMSK with $BT = 1.0$.

The transmit time of the synch-burst has a fixed relation to the first radio burst of the succeeding core frame. It depends on the used TSMA-pattern group. The time interval from the center of the synch burst to the center of radio burst 0 of the succeeding core frame is given by

- $T_{sb} = 337$ modulation symbol intervals for TSMA-pattern group 1 and 2
- $T_{sb} = 66$ modulation symbol intervals for TSMA-pattern group 3.

The uplink synch burst shall help to reduce the base station receiver complexity. In the optimal case, the base station needs only to search for this synch-burst within a limited frequency band. After having received and successfully demodulated the synch-burst, it switches to telegram splitting mode, and needs to search for a specific TSMA-pattern with a known carrier frequency offset, estimated from the synch-burst. The price to pay, however, is a reduction of receiver sensitivity. The required signal-to-noise ratio for receiving a single synch-burst transmitted over a static AWGN-channel is significantly higher than for receiving a core frame with telegram splitting and channel coding.

6.2 Downlink Synchronization Burst

Also for the downlink a special synchronization burst may optionally be used. It is transmitted before the core frame and before each block of the extension frame. It consists of a single radio burst with a structure as shown in Figure 35. It contains almost no information. All fields are filled with fixed bit patterns. The center field is filled with the same pilot sequence as used in the uplink for the radio bursts of the core frame.

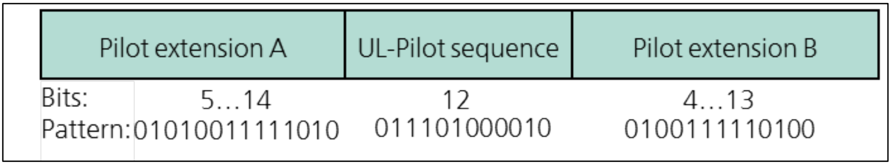


Figure 35: Downlink synch-burst data unit

Only the burst length is adapted to the length of the radio bursts of the succeeding block according to the following algorithm:

For the core frame the synch-burst data unit has a fixed length of $n_{sb} = 21$.

For each block of the extension frame the length depends on the number n_b of bytes per block which can be obtained from the MPDU size by relation (20). The synch burst length can be calculated from

$$n_{sb} = \begin{cases} 21 & \text{for } n_b \le 7 \\ 21 + (n_b - 7) & \text{for } n_b > 7 \end{cases} \qquad (21)$$

The number of bits in the pilot extension fields A and B can be calculated according to the following formulas:

$$\begin{aligned} n_{\mathrm{PS\_Ext\_A}} &= \lceil (n_{sb} - 12)/2 \rceil \\ n_{\mathrm{PS\_Ext\_B}} &= \lfloor (n_{sb} - 12)/2 \rfloor \end{aligned} \qquad (22)$$

In case of truncation, the outer symbols of the pilot extension fields are omitted.

The purpose of the downlink synch burst might be questionable, because the downlink receiver has all information necessary to receive the downlink message anyway. However, it might help to adjust the automatic gain control (AGC) before the 1st burst of the following message frame is received. This might help to adjust the input of the analog to digital converter (ADC) before the radio bursts with the relevant data are received.

References

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[2] Kilian, G.; Breiling, M.; Petkov, H.; Lieske, H.; Beer, F.; Robert, J.; Heuberger, A.: »Increasing Transmission Reliability for Telemetry Systems using Telegram Splitting«, IEEE Transactions on Communications, Vol. 63, No. 3, March 2015

[3] IEEE Std 802.15.4-2011: »IEEE Standard for Local and metropolitan area networks; Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)«