Performance Analysis of Different LoRaWAN Frequency Bands for mMTC Scenarios

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***Abstract*—The possibility of utilizing different frequencies for the LoRaWAN is a key component which, together with the other parameters, i.e., (i) bandwidth, (ii) spreading factor, (iii) coding rate, and (iv) transmission power, defines the communication performance. In this paper, we present the substantive improvements for both the end devices and the radio access network (gateways) to enhance the data rates and decrease the communication latency. The implementation changes were made for the publicly available LoRaWAN module "signetlabdei" for Network Simulator 3. Utilizing the frequency 2.4 GHz, the transmission time in the LoRaWAN network has improved by 80 % decreasing from 75 ms to 14 ms. The frequency 2.4 GHz for the EU region also showed the best performance due to the extended bandwidth (transmission success above 90 %) in the case of the mMTC scenario with thousands of devices deployed. Together with the updated LoRaWAN module, the reported results are expected to serve as a building block for mMTC-oriented simulation scenarios.**

***Keywords*—LoRaWAN, massive machine-type communication, network simulator 3, low-power wide area networks**

I. INTRODUCTION

Over the decade, the paradigm of communication technologies for performance-limited, battery-powered, and relatively cheap devices has evolved rapidly. Starting with the simple sensors, e.g., for the temperature and humidity measurements, continuing through the position trackers, the market moved to the point where the intelligent devices transfer complex data reliably and enable the true next-generation scenarios within the industrial internet of things (IIoT) landscape. With the increasing number of communication scenarios, the requirements related to the communication parameters of the utilized low-power wide-area networks (LPWAN) are becoming more challenging [1].

To fulfill the expected communication parameters, it is possible to choose from two main groups of the LPWANs. The communication technologies operating in the licensed frequency spectrum stand for the representatives of the so-called cellular IoT. Nowadays, the main ones are the narrowband IoT (NB-IoT) and LTE Cat-M. On the opposite side, the license-exempt communication technologies, e.g., Sigfox and LoRaWAN, enable the wireless transmissions over the shared frequency spectrum [2].

This paper focuses on long range technology for wide area networks (LoRaWAN), a leading LPWA technology utilizing unlicensed frequency bands. It uses the long range (LoRa) modulation, which is a form of frequency-shifted chirp spread spectrum (CSS) modulation. The performance parameters can be adjusted by several factors: (i) frequency/bandwidth, (ii) spreading factor, (iii) coding rate, and (iv) transmission power. We extend the module introduced [3] for the Network Simulator 3 (NS-3) to implement the support for the remaining frequency bands as the current version of the module does support only the frequency 868 MHz in the sub-GHz part of the spectrum. Specifically, two frequency alternatives were implemented: (i) 915 MHz (US band) and (ii) 2.4 GHz (Europe).

TABLE I. KEY PARAMETERS OF LPWAN TECHNOLOGIES IN QUESTION [4], [5], [6], [7], [8], [9].

	LoRaWAN	**Sigfox**	**NB-IoT**
Coverage (MCL)	157 dB	162 dB	164 dB
Technology	Proprietary	Proprietary	Open LTE
Spectrum	Unlicensed	Unlicensed	Licensed
Frequency	433, 868, 915 MHz, and 2.4 GHz	868, 915 MHz	700–2100 MHz
Bandwidth	125, 250, 500, 812 kHz	100, 600 Hz	200 kHz
Max. EIRP UL	14 dBm[1]	14 dBm[1]	23 dBm
Max. EIRP DL	27 dBm[1]	14 dBm[1]	23 dBm
Downlink data rate	0.25-21.9 kbps[2]	0.6 kbps	0.5-27.2 kbps
Uplink data rate	0.25-11 kbps[2]	0.1-0.6 kbps	0.3-62.5 kbps[3]
Max. payload UL	242 B	12 B	1600 B
Max. payload DL	242 B	8 B	1600 B
Battery lifetime	10+ years	10+ years	10+ years
Module cost	6 $	3 $	12 $
Security	AES-128	AES-128	LTE Security

[1] The value is relevant for EU.
[2] 50 kbps for FSK modulation.
[3] 3GPP Release 13.

The main contributions of our paper can be summarized as follows:

- Enhancements of the frequency spectrum utilization for EU (868 MHz and 2.4 GHz) and US (915 MHz) regions.
- Implementation of new schemes for the maximum transmission power, i.e., 16 dBm (40 mW) for the EU and 1 W (30 dBm) for the US.

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- Comparison of all three frequencies with respect to the: (i) communication distance, (ii) transmission time, (iii) success rate, and (iv) data rates.

The remainder of this paper is structured as follows. In Section II, we discuss the implementation made to enable the new frequencies. The description of simulation scenario together with the discussion on the obtained results is provided in Section III. Finally, concluding remarks together with lessons learned are provided in Section IV.

II. FREQUENCY SPECTRUM UTILIZATION

LoRaWAN enables the utilization of a wide variety of frequency bands in the unlicensed frequency spectrum. Currently, the bands including 433 MHz, 868 MHz, 915 MHz, and 2.4 GHz are possible to use. On top, two supplementary bands, i.e., 500 MHz and 780 MHz are supported [7].

The EU 868 MHz band consists of 16 communication channels with the bandwidth ranging from 125 kHz to 250 kHz. The duty-cycle follows the legacy rule of the utilization of 1 % of the operational period using the maximal transmission power of 14 dBm (25 mW). These specific conditions limit the maximum size of the transmitted data, which is also bounded by the chosen spreading factor (SF), i.e., ranging from 51 B (SF 7) to 242 B (SF 12). The US 915 MHz band is based on the frequency hopping technique supporting up to 72 channels in the uplink. The bandwidth ranges from 125 kHz to 500 kHz. Compared with the EU 868 MHz, the band limits the time-on-air utilization up to 400 ms and the maximum SF set to 10. Specifically for South Korea and Japan, the utilization of the listen before talk (LBT) is required [7].

The recently introduced EU 2.4 GHz band allows to use three frequencies, i.e., 2.403 GHz, 2.425 GHz, and 2.479 GHz with the channel bandwidth of 812 kHz (this configuration is valid for the EU). The complete list without regional restrictions defines 203 kHz, 406 kHz, 812 kHz, and 1625 kHz of bandwidth. The maximum size of the payload is again connected with the configured spreading factor, i.e., 59 B (SF 12), 123 B (SF 11), and 228 B (SFs 7-10). The parameters for all considered frequency bands are listed in Tables II, III, IV, V, and VI.

In this paper, we selected the publicly available LoRaWAN module "signetlabdei" for Network Simulator 3[1] in which the implementations related to the extension of the supported frequency bands were made [11], [12].

TABLE II. DEFINED DATA RATES FOR THE EU REGION.

Data rate id. [-]	**SF**	**Bandwidth [kHz]**	**Data rate [bps]**	**Payload size [B]**
0	12	125	250	51
1	11	125	440	51
2	10	125	980	51
3	9	125	1760	115
4	8	125	3125	242
5	7	125	5470	242
6	7	250	11000	242

TABLE III. DEFINED DATA RATES FOR THE US REGION.

Data rate id. [-]	**SF**	**Bandwidth [kHz]**	**Data rate [bps]**	**Payload size [B]**
0	10	125	980	11
1	9	125	1760	53
2	8	125	3125	125
3	7	125	5470	242
4	8	500	12500	242
8	12	500	980	53
9	11	500	1760	129
10	10	500	3900	242
11	9	500	7000	242
12	8	500	12500	242
13	7	500	21900	242

TABLE IV. FREQUENCY BANDS UTILIZED FOR THE EU REGION.

Data rate id. [-]	**SF**	**Bandwidth [kHz]**	**Data rate [bps]**	**Payload size [B]**
0	12	812	1200	59
1	11	812	2100	123
2	10	812	3900	228
3	9	812	7100	228
4	8	812	12700	228
5	7	812	22200	228

TABLE V. FREQUENCY BANDS UTILIZED FOR THE US REGION.

Direction	**Number of channels**	**Frequency band [-]**	**Bandwidth [kHz]**	**Data rate id. [-]**
Uplink	64	902.3 – 914.9 MHz divided by block of 200 kHz	125	0 – 3
Uplink	8	903.0 – 914.2 MHz divided by block of 1.6 MHz	500	4
Downlink	8	923.3 – 927.5 MHz divided by block of 600 kHz	500	8 – 13

TABLE VI. THE RECEIVED POWER AND DATA RATE BASED ON THE CONFIGURATION OF THE SPREADING FACTOR AND THE BANDWIDTH IN THE CASE OF 2.4 GHZ BAND.

	Bandwidth [kHz]							
	203		**406**		**812**		**1625**	
SF [-]	P_{RX} [*dBm*]	R_D [*kbit/s*]	P_{RX} [*dBm*]	R_D [*kbit/s*]	P_{RX} [*dBm*]	R_D [*kbit/s*]	P_{RX} [*dBm*]	R_D [*kbit/s*]
7	-115	11.1	-113	22.2	-112	44.41	-106	88.87
8	-118	6.34	-116	12.69	-115	25.38	-109	50.78
9	-121	3.57	-119	7.14	-117	14.27	-111	28.56
10	-124	1.98	-122	3.96	-120	7.93	-114	15.87
11	-127	1.09	-125	2.18	-123	4.36	-117	8.73
12	-130	0.595	-128	1.19	-126	2.38	-120	4.76

The general architecture of the realized scenario is depicted in Fig. 1 and the list of updated classes of LoRaWAN protocol stack is shown in Fig. 2.

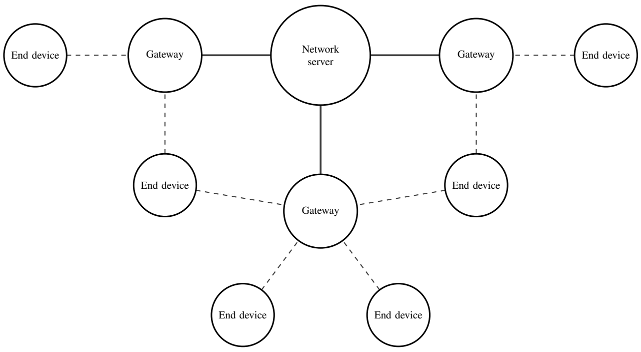

Fig. 1. An example of the LoRaWAN network infrastructure.

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[1] In "signetlabdei" module, the received power is calculated by the link measurement model considering the sensitivity of the module SX1301 [10].

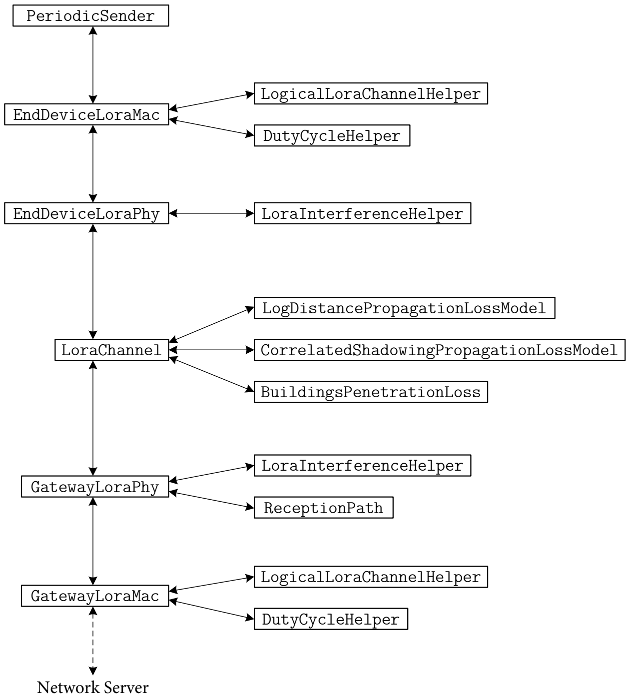

Fig. 2. A set of utilized classes for the LoRaWAN protocol stack in the NS-3.

The implementation of the frequency bands 915 MHz and 2.4 GHz was done following the given LoRa Alliance parameters [7]. As the radio network part of the topology is composed from end devices and gateways, the changes were made for all entities, i.e., mainly in the LoRawanMacHelper class. An example of the configuration of the communication channel is shown in Listing. 1.

Listing 1. The configuration of channel parameters for the US 915 MHz frequency band.

```
void
LorawanMacHelper::ApplyCommonUsConfigurations
    (Ptr<LorawanMac> lorawanMac) const
{
  NS_LOG_FUNCTION_NOARGS ();
  LogicalLoraChannelHelper channelHelper;
  channelHelper.AddSubBand (902, 928, 0.015,
      30); //(firstFrequency, lastFrequency,
      DutyCycle, maxTxPower)
  Ptr<LogicalLoraChannel> lc1 =
      CreateObject<LogicalLoraChannel> (903.1,
      0, 4); //(frequency, minDataRate,
      maxDataRate)
  channelHelper.AddChannel (lc1);
  lorawanMac->SetLogicalLoraChannelHelper
      (channelHelper);
  lorawanMac->SetSfForDataRate
      (std::vector<uint8_t>{10, 9, 8, 7, 8});
  lorawanMac->SetBandwidthForDataRate (
     std::vector<double>{125000, 125000,
         125000, 125000, 500000});
  lorawanMac->SetMaxAppPayloadForDataRate (
     std::vector<uint32_t>{30, 61, 133, 230,
         230});
}
```

III. SIMULATION RESULTS

Having the frequency bands in question implemented, we created two simulation scenarios for the performance verification. First, the time for the transmission of the message with the size 23 B was analyzed for three different frequency bands: (i) EU 868 MHz, (ii) US 915 MHz, and (iii) EU 2.4 GHz. For the purpose of this first scenario, only one device and one gateway were enabled in the network. Then, the end device moved away from the gateway in the predefined steps (see Table VII) and the transmission time was measured.

TABLE VII. THE DEPENDENCE OF THE TRANSMISSION TIME ON THE COMMUNICATION DISTANCE AND THE FREQUENCY BAND.

Region:	**EU sub-GHz**	**US 915 MHz**	**EU 2.4 GHz**
Distance [m]	**Transmission time [ms]**		
5	71.952	33.424	11.090
50	72.102	33.574	11.240
100	72.269	33.741	11.407
150	72.436	33.908	11.574
200	72.603	34.075	11.741
250	72.769	34.241	11.907
300	72.936	34.408	12.074
350	73.103	34.575	12.241
400	73.270	34.742	12.408
450	73.437	34.909	12.575
500	73.603	35.075	12.741
600	73.937	35.409	13.075
700	74.270	35.742	13.408
800	74.604	36.076	13.742
900	74.938	36.410	14.076
1000	75.271	36.743	14.409

The results shown in Fig. 3 confirm the initial assumptions, i.e., the wider bandwidth and higher frequency, the lower time needed for the data transmission as there is only line-of-sight (LOS) communication. Therefore, the surrounding buildings do not influence the signal propagation, and the gathered data highlight the differences in the data rates. Utilizing the frequency 2.4 GHz, the transmission time has improved by 80 % decreasing from 75 ms to 14 ms.

The second scenario points out the situation in the network where the number of end devices increases steadily. For all three frequency bands, the simulation was done in a way that only one gateway and one remote server are in the network. The end devices connect to the gateway and attempt to send data toward the remote node. In this scenario, all end devices have the fixed communication distance to the gateway set to 1 km.

As can be seen in Fig. 4 the number of end devices was increased continuously by 200, and the success rate of the data transmission was measured. Contrary to the first scenario, each end device sent two messages of size 23 B. The Fig. 4 indicates the main drop of the performance (success rate) occurred once more than one thousand of end devices were connected to the network. In case of the US 915 MHz and EU sub-GHz frequency bands, the success rate drops bellow 90 %. On the contrary, the EU 2.4 GHz frequency band delivered a success

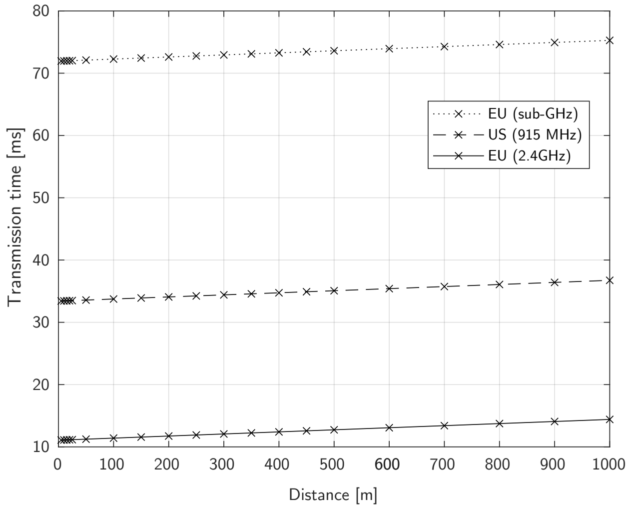

Fig. 3. The dependence of the transmission time based on the utilized frequency band and communication distance.

rate above 90 % even in the case of two thousand connected end devices. The frequency 2.4 GHz for the EU region showed the best performance due to the extended bandwidth.

On top of the indication of the success rate mentioned in Fig. 4, the Table VIII lists also the number of sent messages, successfully received messages, and comparison of those statistics for all three frequency bands. Considering this specific configuration of massive number of connected devices toward one gateway, the LoRaWAN technology can be considered for mMTC scenarios with thousands of devices being deployed.

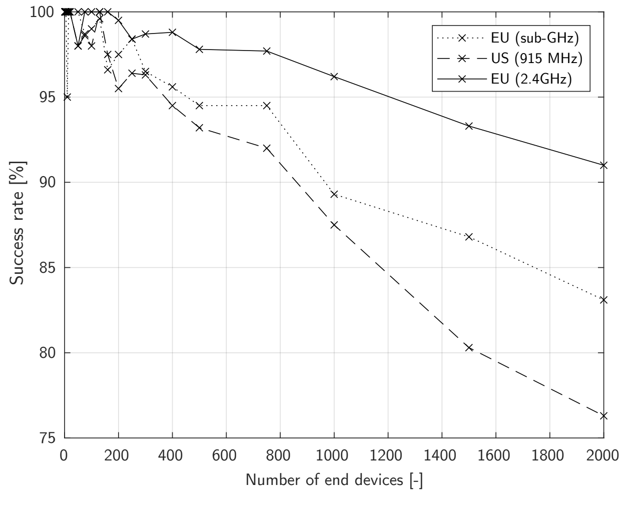

Fig. 4. The dependence of the transmission success rate on the utilized frequency band and number of end devices.

IV. CONCLUSIONS AND LESSONS LEARNED

In this paper, we detailed the performance of the LoRaWAN network in case of the utilization of new frequency bands using the NS3 and the LoRaWAN module "signetlabdei". Besides the already implemented frequency band 868 MHz for EU region, we have implemented the US frequency band 915 MHz and the EU frequency band 2.4 GHz. Utilizing the frequency 2.4 GHz, the transmission time in the LoRaWAN network has improved by 80 % decreasing from 75 ms to 14 ms. Furthermore, the frequency 2.4 GHz for the EU region also showed the best performance due to the extended bandwidth (transmission success above 90 %) in the case of the mMTC scenario with thousands of end devices deployed.

TABLE VIII. DETAILED STATISTICS FROM THE SECOND SCENARIO.

Number of		**Received messages in band EU (sub-GHz)**		**Received messages in band US (915 MHz)**		**Received messages in band EU (2.4 GHz)**	
End devices [-]	**Transmitted messages [-]**	[-]	[%]	[-]	[%]	[-]	[%]
1	2	2	100.0	2	100.0	2	100.0
3	6	6	100.0	6	100.0	6	100.0
5	10	10	100.0	10	100.0	10	100.0
10	20	19	95.0	20	100.0	20	100.0
15	30	30	100.0	30	100.0	30	100.0
20	40	40	100.0	40	100.0	40	100.0
50	100	100	100.0	98	98.0	98	98.0
75	150	148	98.7	148	98.7	150	100.0
100	200	198	99.0	196	98.0	200	100.0
130	260	259	99.6	260	100.0	260	100.0
160	320	309	96.6	312	97.5	320	100.0
200	400	390	97.5	382	95.5	398	99.5
250	500	492	98.4	482	96.4	492	98.4
300	600	579	96.5	578	96.3	592	98.7
400	800	765	95.6	756	94.5	790	98.8
500	1000	945	94.5	932	93.2	978	97.8
750	1500	1418	94.5	1380	92.0	1466	97.7
1000	2000	1785	89.3	1750	87.5	1924	96.2
1500	3000	2605	86.8	2410	80.3	2800	93.3
2000	4000	3325	83.1	3050	76.3	3640	91.0

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