Analysis of Capacity and Scalability of the LoRa Low Power Wide Area Network Technology

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***Abstract*—In this paper we discuss and analyze the recently proposed LoRa low power wide area network (LPWAN) technology when used under the European frequency regulations. First of all, we derive the performance metrics of a single LoRaWAN end device, namely uplink throughput and data transmission time. Then we analyze for several illustrative application scenarios the maximum number of end devices which can be served by a single LoRaWAN base station and discuss the spatial distribution of these devices. It is shown that subject to the channel composition and application requirements, a single cell may include several millions of devices. Also, we show that the capacity of the uplink channel available to a LoRaWAN node strongly depends on the distance from the base station and does not exceed 2 kbit/s. In the concluding section we summarize and discuss the obtained results, and point out few issues which need to be taken into account when making an application using LoRa or deploying a LoRa network.**

Keywords—LoRa; LPWAN, long range; low power; wide area network; IoT; wireless; communication.

I. Introduction

The low power wide area networks (LPWANs) represent a new trend in the evolution of the wireless communication technologies. Unlike the traditional broadband, these systems do not focus on enabling high data rates per device. Instead, the key performance metrics defined for these systems are *energy efficiency, scalability* and *coverage*.

The LPWANs of today are typically seen as cellular networks composed of the end devices (ED) and the base stations (BS). The EDs are connected to and served by the BS thus forming a star-topology network around them as illustrated in Fig. 1. Typically, an ED communicates only to a BS and not with the other EDs. Unlike the traditional cellular networks for which the amount of downlink traffic exceeds the uplink, for LPWANs the uplink traffic dominates.

Today several competing LPWAN technologies are present on the market. The first option is the ultra-narrowband Sigfox technology operating in 868/902 MHz license-free industrial, scientific and medical (ISM) radio band. The company acts both as the technology and as a service provider and has already deployed its BSs around Europe [1]. The other option is Weightless technology, which consists of the three protocols [2]. Weightless-W is designed to operate in between 470MHz–790MHz TV white space spectrum providing 1kbit/s to 10Mbit/s throughput subject to link budget and settings. Weightless-P aims at providing ultra-high performance LPWAN connectivity. The technology can be used over the broad range of license-exempt sub-GHz ISM bands employing frequency and time division multiple access in 12.5 kHz narrow band channels. Weightless-N is an ultra-narrowband technology based on differential binary phase shift keying (BPSK). The third option is Long Range (LoRa) WAN based on LoRa proprietary spread spectrum technique and Gaussian Frequency Shift Keying (GFSK) [3]. The fourth option is the Long Term Evolution for machine-to-machine (LTE-M) and specifically Narrowband LTE-M (NB LTE-M) [4], which is backed by the traditional telecom and is expected to enter the competition soon. Among the other technologies featuring similar characteristics can be listed e.g., Ingenu/On-Ramp, SilverSpring's Starfish, Cyan's Cynet, Accellus, Telensa, nwave and Waviot (refer e.g., to [5] and [6] for further details). Unfortunately, the information about them available in open access is very scarce.

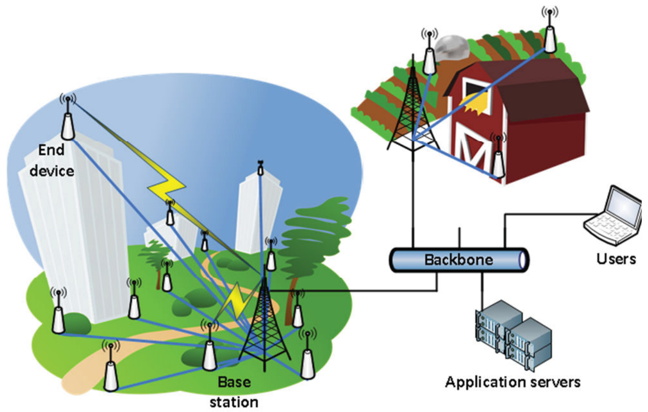

Fig. 1. Typical LPWAN network landscape

In this paper we focus specifically on the LoRa technology and namely the problem of network scalability. The major contribution of the paper is the provided in-depth analysis of the LoRa communication technology, the potential throughput available to a single LoRa ED and the number of devices which can be served by a single BS for few different scenarios. Finally, we provide some discussion and point out a few potential bottlenecks of the technology.

Since the LPWANs in general and LoRa technology in particular are rather new, they have not got much of attention

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Table I. LoRaWAN data rates settings and frames characteristics

Data rate (DR)	SF	Band width, kHz	Modu-lation	maximum MACPayload size, bytes	Maximum FRMPayload size[1], bytes	Shortest downlink frame ToA, s	Longest downlink frame ToA, s	Shortest uplink frame ToA, s	Longest uplink frame ToA, s
0	12	125	LoRa	59	51	0.991	2.793	1.155	2.793
1	11	125	LoRa	59	51	0.578	1.479	0.578	1.561
2	10	125	LoRa	59	51	0.289	0.698	0.289	0.698
3	9	125	LoRa	123	115	0.144	0.677	0.144	0.677
4	8	125	LoRa	250	242	0.072	0.697	0.082	0.707
5	7	125	LoRa	250	242	0.041	0.394	0.041	0.400
6	7	250	LoRa	250	242	0.021	0.197	0.021	0.200
7	n/a	150	GFSK	250	242	0.0032	0.0421	0.0035	0.0424

[1] - given that *$FHDR_{OPTS}$*=0

from the Academic community yet. So far the authors are aware of only four research papers addressing LoRa technology. In [7] the authors evaluated the coverage of LoRa communication while using high-bandwidth (i.e., 250 kHz) LoRa (with spreading factor (SF) of 10) and Gaussian Frequency Shift Keying (GFSK) modulated radio signals. The similar experiments this time for low-bandwidth LoRa were done by us and reported in [8] for outdoor and in [9] for indoor cases. The performance and indoor through-obstacle penetration of the LoRa modulation in the 2.4 GHz frequency band was evaluated in [10].

II. LoRa Technology

Technically, the LoRa LPWAN solution includes two major components. The first one is LoRa modulation, which is based on chirp spread spectrum (CSS) scheme that uses wideband linear frequency modulated pulses whose frequency increases or decreases based on the encoded information [11]. The use of signals with high bandwidth-time product (BT>1) should make the radio signals resistant against in band and out of band interferences, whilst the use of sufficiently broadband chirps should help to fight against heavy multipath fading characteristic for indoor propagation and urban environments [12]. As a result, the maximum power budget for LoRa operating in EU 868 MHz can exceed 150 dB thus enabling to obtain long communication ranges or to reduce the transmit power thus saving the energy of EDs. Finally, the used modulation scheme is also expected to be robust against the Doppler effect thus improving the performance of communication with mobile objects. Additionally, LoRa modulation includes a variable cyclic error correcting scheme which improves the robustness of the communication by adding some redundancy [12]. To improve the spectral efficiency and increase the capacity of the network, LoRa modulation features six orthogonal spreading factors (SF) resulting in the different data rates. This enables multiple differently spread signals to be transmitted at the same time on the same frequency channel [12] without degrading the communication performance and trading the on-air time for the communication range.

The second component is the LoRaWAN network protocol which is optimized specifically for energy limited EDs [3]. As discussed earlier, the LPWAN typically has star topology and consists of BSs relaying data messages between the EDs and an application server. The BSs can be connected to the central server via backbone internet protocol (IP) based link, and the

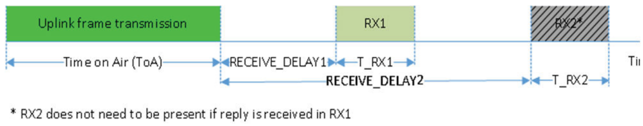

Fig. 2. LoRaWAN class A ED uplink transmission phases

wireless communication based on LoRa or GFSK modulation is used to move the data between EDs and the BSs. The communication is spread over the different sub-GHz frequency channels (433 and/or 780/868/915 MHz) depending on the local frequency regulations. Each ED can start sending its data at any moment of time using any available data rate, unless specifically instructed otherwise by the BS. Note that LoRaWAN does not use the clear channel assessment (CCA) mechanisms and relies exclusively on the ED duty cycle based channel access mechanism. For this, each ED tracks the time spent transmitting in each frequency channel and backs off the transmission in this channel accounting for the imposed restrictions. The ED selects the frequency channel to use in pseudo-random manner [3] for each next packet to be transmitted.

The 1.0 version of the LoRaWAN specification [3] defines three classes of EDs named A, B and C. The implementation of class A functionality is obligatory, whilst classes B and C are optional. For the EDs of class A each uplink transmission is followed by the two receive windows (RX1 and RX2) as this is shown in Fig. 2. Either of these windows can be used by the BS for transferring the data to the respective ED. Note that the receive windows may have the frequency channel and the SF differing from the ones used for sending the uplink packet. In case the ED gets a reply in RX1, RX2 can be omitted.

The devices of class B in addition to RX1 and RX2 opened after uplink frames also have special receive windows at scheduled times. For maintaining the synchronization and providing the time reference to EDs the BS periodically transmits beacons. Finally, EDs of class C stay in receive almost all the time. Further in this paper we will focus specifically on EDs of class A.

Note that for Europe LoRaWAN specifies two possible frequency band options, namely 433 and 868 MHz ISM bands. Since the latter one is broader and has sub bands with less strict duty cycle limitations, we assume use of this band for our analysis. For this band the LoRaWAN specification enables use of totally eight physical layer (PHY) options listed in Table I. The first six of them are based on LoRa modulation

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Table II. LoRaWAN ED performance for the different data rates

Data rate (DR)	No RX slots				ACK in RX1[1]				No ACK in RX2[2]			
	Minimum packet period, s	PHY throughput, bit/s	APP throughput, bit/s	Max. duty cycle, %	Minimum packet period, s	PHY throughput, bit/s	APP throughput, bit/s	Max. duty cycle, %	Minimum packet period, s	PHY throughput, bit/s	APP throughput, bit/s	Max. duty cycle, %
0	2.7935	183.3	146.1	100	4.78	107.0	85.3	58.4	5.0	103.3	82.3	56.4
1	1.5606	328.1	261.4	100	3.14	163.2	130.0	49.7	3.7	137.5	109.5	41.9
2	0.6984	733.1	584.2	100	1.99	257.7	205.3	35.1	2.9	178.9	142.5	24.4
3	0.6769	1 512.9	1 359.2	100	1.82	562.3	505.1	37.2	2.8	360.5	323.9	23.8
4	0.7071	2 885.1	2 738.1	100	1.78	1 146.5	1 088.1	39.7	2.9	710.6	674.4	24.6
5	0.3996	5 104.9	4 844.7	100	1.44	1 415.8	1 343.7	27.7	2.6	795.8	755.2	15.6
6	0.1998	10 209.8	9 689.3	100	1.22	1 671.6	1 586.3	16.4	2.4	863.1	819.1	8.5
7	0.0424	48 113.2	45 660.4	100	1.05	1 951.0	1 851.6	4.1	2.0	998.2	947.3	2.1

[1]-assumed that the acknowledgement frame has no payload and is transmitted using the same DR (i.e., best-case scenario)
[2]-assumed that RX2 is open with DR0 settings (the default setting according to [3])

$$ToA = T_{preamble} + T_{packet} = T_{symb}\left(L_{preamble} + L_{PHDR} + L_{PHDR\_CRC} + L_{PHY\_payload} + L_{PHY\_CRC}\right) =$$
$$= \begin{cases} \dfrac{2^{SF}}{BW}\left((NP + 4.25) + \left(SW + \max\left(ceil\left[\dfrac{8PL - 4SF + 28 + 16CRC - 20IH}{4(SF - 2DE)}\right](CR + 4), 0\right)\right)\right) & , LoRa \\ \dfrac{8}{DR}\left(NP + SW + PL + 2CRC\right) & , GFSK \end{cases} \quad (1)$$

with 125 kHz bandwidth and SF ranging from 7 to 12. The two last ones are based on LoRa modulation with 250 kHz bandwidth and SF of 7, and GFSK with 50 kbps rate.

III. Analysis of LoRaWAN Performance

According to [13] a LoRaWAN frame consists of a preamble with synchronization word, physical header (PHDR) with additional header CRC (PHDR_CRC) for LoRa modulation, the payload and the CRC checksum. The time-on-air (ToA) is given by (1), where *NP* is the number of preamble symbols (*NP*=8 for LoRa-modulated channels or *NP*=5 bytes for GFSK channel), *SW* is the length of synchronization word (*SW*=8 bits for LoRa and 3 bytes for GFSK modulation), *PL*>0 is the number of PHY payload bytes, *CRC* and *IH* specify the presence of CRC and PHY header, respectively, (LoRaWAN specification prescribes *CRC*=1 and *IH*=0 for uplink, *CRC*=0 and *IH*=0 for downlink). For LoRa modulation *DE* indicates use of data rate optimization which adds a small overhead to increase robustness to reference frequency variations over the timescale of the LoRa frame (obligatory for *DR0* and *DR1*) and *CR*=1 (corresponds to 4/5 coding rate). For GFSK modulated frame *DR*=50 kbit/s.

Based on the frame formats defined in [3], the length of the PHY layer payload in bytes is given by:

$$\begin{aligned} PL &= MHDR + MACPayload + MIC = MHDR + FHDR_{ADDR} + FHDR_{FCTRL} \\ &+ FHDR_{CNT} + FHDR_{OPTS} + FPort + FRMPayload + MIC = \\ &= 12 + FHDR_{OPTS} + FPort + FRMPayload \end{aligned} \quad (2)$$

where *MHDR*=1 is the length of MAC header, $FHDR_{ADDR}$=4 is the length of ED address field of the frame header (FHDR), $FHDR_{FCTRL}$=4 and $FHDR_{CNT}$=4 are the lengths of the FHDR's frame control and frame counter fields, respectively, identifier (present if frame payload FRMPayload field is not empty), MIC=4 is the message integrity code. Note that the maximum length of the frame payload for a LoRa ED communicating directly with a BS depends on the used data transmission mode as shown in Table I. $FHDR_{OPTS}$ is the length of the optional FHDR field carrying MAC commands, *FPort*=1 is the application specific port The ToA values presented in the four rightmost columns were obtained using (1) and (2) for *FRMPayload*=0 (shortest frame) and the maximum valid payload (longest frame).

A. Maximum Uplink Throughput for Single End Device

As this was already discussed, LoRaWAN prescribes an ED to open two short receive windows (RX1 and RX2) following each uplink transmission as illustrated in Fig. 2. According to [14] for LoRa modulation the duration of a RX slot should exceed 5 symbols with the DR of the channel where the response is expected and 8 bytes for GFSK channel. The delay between the end of frame's transmission and the start of RX1 can vary, but the minimum delay is one second. If required, RX2 should start exactly one second after the start of RX1. Note that according to [3] an ED *is prohibited to transmit another uplink packet before it either has received a downlink message in RX1 or RX2, or RX2 has expired.* Moreover, if an ED has not received the acknowledgement in RX1 or RX2 and desires to re-transmit a packet, it has to wait for at least *ACK_TIMEOUT* seconds (two seconds by default) before starting the transmission [3]. Taking all these into consideration, in Table II we provide an estimation of time required for transferring a data frame and the maximum PHY and application (APP) layer throughputs for the three cases: the absence of RX slots (given for reference, since this mode is not LoRaWAN-compatible), reception of acknowledgement in a short packet in RX1 in a the same DR channel, and non-acknowledged transmission. The values were calculated for the frame durations given in Table I.

The presented results show that the obligatory RX windows for downlink communication drastically reduce the throughput of an ED operating in LoRaWAN. As one can see, at best a mere 2 kbit/s of data can be streamed by a LoRa ED uplink. Besides, the use of default parameters (i.e., DR0 for RX2 slot) may negatively affect the lifetime of a LoRa ED. This happens due to the fact that the duration of a DR0 symbol is 32.768 ms which makes T_RX2 alone 164 ms long.

Table III. FICORA frequency regulations [15] and obligatory LoRaWAN channels in EU 863-873 MHz band

Frequency band, MHz	Duty cycle, %	Maximum power, mW ERP	LoRaWAN obligatory channels, MHz	LoRaWAN join request channels, MHz	Max 125 kHz LoRa channels[2]	Max 250 kHz LoRa channels[2]	Max 150 kHz GFSK channels[2]
863–868.6,868.7–869.2,869.4–869.65,869.7–870	0.1	25	-	864.1[1],864.3[1],864.5[1]	32	19	37
868.0–868.6	1	25	868.1[1],868.3[1],868.5[1]	868.1[1],868.3[1],868.5[1]	3	2	4
868.7–869.2	0.1	25	-	-	2	1	3
869.4–869.65	10	500	-	-	1	0	1
869.7–870.0	1	25	-	-	1	0	2
870.0–873.0	1	25	-	-	15	10	20
Total					47	29	57

[1]- LoRa modulation, 125 kHz bandwidth, DR0-DR5

[2]- the actual bandwidth of 200 kHz for 125 kHz LoRa channel and 300 kHz for 250 kHz LoRa channel (similar to [16]) and 150 kHz for GFSK channel are assumed.

Table IV. Maximum throughput per LoRaWAN channel and ED

Data rate (DR)	Bandwidth, kHz	Maximum APP throughput per channel, bit/s	Maximum APP throughput per ED per channel, bit/s		
			10% duty cycle	1% duty cycle	0.1% duty cycle
0	125	146.1	14.61	1.46	0.15
1	125	261.4	26.14	2.61	0.26
2	125	584.2	58.42	5.84	0.58
3	125	1 359.2	135.92	13.59	1.36
4	125	2 738.1	273.81	27.38	2.74
5	125	4 844.7	484.47	48.45	4.84
0-5 cumulative[1]	125	9 933.6	n/a	n/a	n/a
6	250	9 689.3	968.93	96.89	9.69
7	150	45 660.4	1 851.6[2]	456.6	45.66

[1]- given that the spreading factors for DR0-DR5 are orthogonal, the transmissions with different SF may coexist in the same channel at the same time

[2]- due to the need for opening RX windows after each frame, the maximum possible duty cycle is 4.1% (see Table II, acknowledged transmission)

Another factor limiting the performance of LoRaWAN is the restrictions imposed by the frequency regulations. Since LoRaWAN does not employ CCA, it has to cope with rather tough duty cycle restrictions imposed by the regulations. The channels and the restrictions based on EU regulations [15] are summarized in the three leftmost columns of Table III. In addition, the table provides an estimation of the total number of channels of each type potentially available for LoRaWAN.

The maximum throughput for each LoRaWAN DR channel option and for a single ED under different duty cycle restrictions are summarized in Table IV. Note that the LoRaWAN specification imposes more strict requirements regarding duty cycle handling than the ones defined in [15]. Namely, according to [3] after transmitting a frame on a sub channel, this sub channel cannot be used for the next $Toff_{subband} = ToA(1/DutyCycle_{subband} - 1)$ seconds, where ToA is time on air for the transmitted packet and $DutyCycle_{subband}$ is the maximum duty cycle permitted for the subband, which is given in Table III. Meanwhile, [15] prescribes to estimate the duty cycle relative to a one hour period. The major outcome of this is the impossibility for a LoRaWAN device to transfer bursts of data in the same subchannel. Due to this reason, the results for the throughput presented in Table IV should be treated as the long-term average for the particular DR, whilst the short-term peak throughputs for acknowledged and unacknowledged transmissions over multiple channels can be derived from Table II.

B. *LoRaWAN Capacity*

The results presented in Tables II and IV can be used for estimating the maximum number of EDs served by a single BS. In Table V we present the results of maximum LoRaWAN cell capacity analysis for several characteristic machine type communications use cases derived from [17]. The results are given for unacknowledged mode uplink transmission by class A devices for the three different network configurations. Namely the cases of only three obligatory 125 kHz LoRa modulated channels (see Table III), six 125 kHz LoRa channels, or six 125 kHz LoRa channels plus one 250 kHz LoRa and one GFSK channel (same network configuration as in [18]) were investigated. The results were obtained using (1) and (2), assuming that all DR0-DR5 are used in each 125 kHz LoRa channel. Note that in the two rightmost columns of Table V the results are given for the two scenarios. The first one is the maximum capacity which can be theoretically obtained under perfect synchronization and scheduling of the nodes. Nonetheless, LoRaWAN does not possess any synchronization mechanism enabling to achieve this. Instead, the ED are assumed to access the channel randomly in a pure ALOHA fashion. It is well known [19] that the optimal capacity for this case is 0.5/e times the maximum, as shown in the rightmost column of Table V.

Based on the LoRa channel attenuation model for suburban areas from [9] and assuming the sensitivities of BS spatial distribution for the optimal number of EDs under ALOHA channel access assumption. The respective results are presented in Table VI and Fig. 3.

The presented results clearly show that the majority of the EDs need to be located in the vicinity of the BS, i.e. within the first few zones. Less than 10 percent of the EDs can reside at a

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Table V. Capacity of a LoRaWAN cell

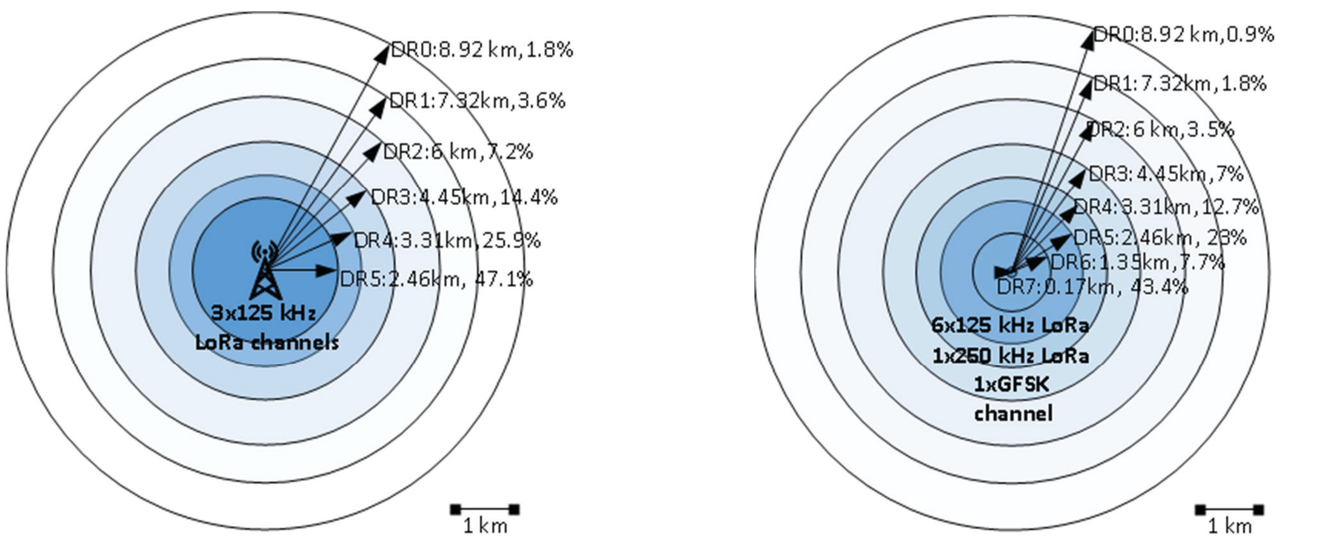
Scenario	Average message transaction rate, s^{-1}	Average message size , byte	Network configuration: Number of 125 kHz LoRa channels	Network configuration: Number of 250 kHz LoRa channels	Network configuration: Number of GFSK channels	Cell capacity, number of EDs: Maximum under perfect synchronization	Cell capacity, number of EDs: Optimal for pure Aloha access
Roadway signs	3,33E-02	1	3	0	0	4 017	739
	3,33E-02	1	6	0	0	8 034	1 478
	3,33E-02	1	6	1	1	15 928	2 930
Traffic lights or traffic sensors	1,67E-02	1	3	0	0	8 187	1 506
	1,67E-02	1	6	0	0	16 374	3 012
	1,67E-02	1	6	1	1	34 715	6 385
House appliances	1,16E-05	8	3	0	0	9 722 253	1 788 309
	1,16E-05	8	6	0	0	19 444 506	3 576 617
	1,16E-05	8	6	1	1	39 778 804	7 316 902
Credit machine in a shop	5,56E-04	24	3	0	0	142 167	26 150
	5,56E-04	24	6	0	0	284 334	52 300
	5,56E-04	24	6	1	1	568 140	104 504
Home security	1,67E-03	20	3	0	0	52 569	9 670
	1,67E-03	20	6	0	0	105 138	19 339
	1,67E-03	20	6	1	1	208 775	38 402

Table VI. Distribution of ED in a LoRaWAN cell assuming optimal number of EDs with ALOHA access

Network config.	DR	Budget [1], dB	Range, km	Scenario 1: 1 byte packet every 30 seconds			Scenario 2: 8 byte packet once a day			Scenario 3: 20 byte packet every 10 min		
				Number of EDs[2]	Node density, EDs/km²	% of EDs	Number of EDs[2]	Node density, EDs/km²	% of EDs	Number of EDs[2]	Node density, EDs/km²	% of EDs
3x125 kHz LoRa channels	5	138	2.46	357	18,9	48,3	842 710	44 499,6	47,1	4 602	243,0	47,6
	4	141	3.31	200	5,8	27,1	463 280	13 486,5	25,9	2 477	72,1	25,6
	3	144	4.45	100	1,6	13,5	257 236	4 128,3	14,4	1 341	21,5	13,9
	2	147	6.00	57	0,5	7,7	128 618	1 137,9	7,2	731	6,5	7,6
	1	149	7.32	25	0,1	3,4	64 309	382,5	3,6	335	2,0	3,5
	0	151	8.92	0	0,0	0,0	32 154	128,6	1,8	182	0,7	1,9
3x125 kHz LoRa 1x250 kHz LoRa 1xGFSK channel	7	111	0.17	1 452	16 301,6	45,8	3 178 478	35 684 788,8	43,4	15 994	179 564,7	41,6
	6	132	1.35	238	41,4	7,5	561 806	97 612,5	7,7	3 068	533,1	8,0
	5	138	2.46	714	37,7	22,5	1 685 420	88 999,1	23,0	9 205	486,1	24,0
	4	141	3.31	401	11,7	12,7	926 561	26 973,1	12,7	4 955	144,2	12,9
	3	144	4.45	200	3,2	6,3	514 472	8 256,5	7,0	2 683	43,1	7,0
	2	147	6.00	114	1,0	3,6	257 236	2 275,9	3,5	1 462	12,9	3,8
	1	149	7.32	50	0,3	1,6	128 618	765,1	1,8	670	4,0	1,7
	0	151	8.92	0	0,0	0,0	64 309	257,2	0,9	365	1,5	1,0

[1]- Transmit power 14 dBm, sum of TX and RX antenna gains is 0 dBi

[2]- $N_{ED}(DR) = floor[N_{ch}(DR)T_{report}/ToA(DR,n)]$ if frequency regulations are met and 0 otherwise. Here $N_{ch}(DR)$ is the number of the available frequency channels for the particular *DR*, T_{report} is the packet report period, *ToA*(*DR,n*) is on-air time for the particular data rate and payload length *n*



a)BS with 3 obligatory 125kHz LoRa channels b)BS with 3 125 kHz LoRa, 1 250 kHz LoRa and one GFSK channel

Fig. 3. Distribution of the EDs in a LoRaWAN cell (% of the total number, single 8-byte packet from an ED per day)

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distances over 5 km. Also, as can be seen from Table VI, the density of the EDs in the different zones varies greatly. E.g., one hundred thousands EDs sending one packet per day using DR6 can be placed in each kilometer square. On the other hand, for the very same cell less than three hundred EDs can reside in each square kilometer in a zone covered with DR0. Note that the sensitivity limit used for defining the coverage areas for various DRs is specified for 0.1% bit error rate (BER). This means that in practice the communication distances can be much higher, although the probability of data errors will be higher as well.

IV. Discussion and Conclusions

In the paper we analyzed the performance of the recently proposed LoRa LPWAN technology. We have shown that following the current specification release, a single end device located close to the base station can feature an uplink data transfer channel of only 2 kbit/s at best. The maximum upload rate available for the more distant nodes decreases with the increase of the distance between the node and the base station and for the most distant nodes drops to mere 100 bits/s in average. The use of duty-cycle based media access mechanism has a twofold effect. On one hand, this enables a LoRaWAN device to send the data with no delays thus reducing the communication latency and energy consumption. Nonetheless, due to sufficiently low data rates especially for LoRa channels with high SF, this is hardly a significant gain. On the other hand, absence of clear channel assesment mechanism increases the probability of packet collisions thus comromising the reliability and may cause long channel access delays due to channel access back off after previous data transfers.

In terms of scalability, the presented results show that a single LoRaWAN cell can potentially serve several millions of devices sending few bytes of data per day. Nonetheless, we have shown that only a small portion of these devices can be located sufficiently far away from the base station. Most of the devices,and especially the ones with higher upload traffic needs, should be located in the vicinity of the base station. Furthermore, this calls for more effective management of the data rates used by the end nodes since only few nodes operating with low data rates can be supported. Another factor which somewhat limits the scalability of the LoRaWAN cell is the use of acknowledgements. Given that the base station is subject to the very same duty cycle restrictions imposed by the frequency regulations, in a dense network it cannot acknowledge each and every packet. Moreover, the base station's duty cycle restrictions need to be also carefully pondered when planning the downlink traffic.

To sum up, one can see that LoRaWAN technology, like any other, has its own strengths and weaknesses. Among the former ones can be noted the high coverage and satisfactory scalability under low uplink traffic. The most critical drawbacks are low reliability, substatial delays and potentially poor performance in terms of downlink traffic. Based on our analysis, we suppose that LoRa can be effectively utilized for the moderately dense networks of very low traffic devices which do not impose strict latency or reliability requirements. Among the possible example use cases are, e.g., non-critical infrastruture or environment monitoring applications.

To the best of authors' knowledge, the current paper is one of the first attempts to shed some light on the network performance of LoRa LPWAN technology. In future we will attempt (subject to availability of the respective technical data) to analyze also the other LPWAN technologies and compare them with LoRa.

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