TROPPO LoRa: TROPospheric Personal Observatory using LoRa signals

Marco Zennaro
mzennaro@ictp.it
The Abdus Salam International Centre for Theoretical Physics
Trieste, Italy

Ermanno Pietrosemoli
ermanno@ictp.it
The Abdus Salam International Centre for Theoretical Physics
Trieste, Italy

Marco Rainone
mrainone@ictp.it
The Abdus Salam International Centre for Theoretical Physics
Trieste, Italy

Daniele Trinchero
daniele.trinchero@polito.it
Politecnico di Torino
Torino, Italy

Mattia Poletti
mattia.poletti@polito.it
Politecnico di Torino
Torino, Italy

Giovanni Colucci
giovanni.colucci@polito.it
Politecnico di Torino
Torino, Italy

ABSTRACT
With the growth of LoRa deployments there are plenty of anecdotal reports of very long wireless links, well beyond the line of sight. Most reports suggest that these links are related to anomalous tropospheric propagation. We developed a platform to study tropospheric links based on TheThingsNetwork, a popular LoRaWAN-based infrastructure. We present some preliminary results and call for the LoT community to participate in this radio propagation experiment.

CCS CONCEPTS
• Networks → Network experimentation.

KEYWORDS
IoT, LoRa, LoRaWAN, TTN, radio propagation, tropospheric

ACM Reference Format:
Marco Zennaro, Ermanno Pietrosemoli, Marco Rainone, Daniele Trinchero, Mattia Poletti, and Giovanni Colucci. 2020. TROPPO LoRa: Tropospheric Personal Observatory using LoRa signals. In Woodstock '18: ACM Symposium on Neural Gaze Detection, June 03–05, 2018, Woodstock, NY. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION
Electromagnetic waves in an homogenous medium travel in a straight line, so a sizable obstacle like the earth curvature will normally block the reception. There are several mechanisms that can change the speed and direction (the velocity) of a radio wave. Whenever there is a discontinuity in the transmission medium there will be a change in the direction of propagation. Depending on the specific type of discontinuity encountered the ray will undergo reflection, refraction, diffraction or scattering. A wave, characterized by many rays, could be affected by a combination of the above.

Reflection is an abrupt change of direction characterized by Snell’s law; the angle of reflection equals the angle of incidence and the speed stays the same. The ray will not penetrate the second medium. In refraction the ray changes direction and speed after penetrating the second medium, and the amount of direction change is proportional to the differences between the refraction indices of the two media. The refraction index n of a medium is the ratio between the speed of the electromagnetic wave in vacuum and the speed in the medium.

2 TROPOSPHERIC PROPAGATION
The atmosphere between ground level and some 12 kilometers is called the troposphere, and in it the pressure, temperature and humidity decrease monotonically with altitude under normal conditions.

Disruptions on the temperature and humidity profiles in the troposphere on frequencies from about 50 MHz to 10000 MHz cause a change in the refraction index that can significantly change the propagation range as shown in Figure 1.

Unusual variations of the humidity and temperature of the air will create a change of the refractive index that can result in a downward bending of the ray that will overcome the earth curvature in what is known as super-refraction [11]. If the refractivity gradient is very high, we can have a very long transmission range in what is called a tropospheric duct.

Since the refraction index of air is very close to 1, a new refractivity parameter N is defined by $N=(n-1)\times10^6$ allowing for the use of more manageable numbers. The value of refractivity N at different heights can be calculated using the formula (1) from [2], where P is atmospheric pressure in hPa, T is the temperature in Kelvin and r is the relative humidity in g/kg.

$$N = 77.6 + \frac{P}{T} + 3.73 \times 10^6 \frac{r \times P}{T^2 \times (622 + r)} \tag{1}$$

The easiest way to obtain P, e and r at different elevations is from the meteorological radiosondes that are routinely launched world-wide [5].

As tropospheric propagation is caused by the deviation from the normal profile of refractivity with altitude [2], we use the gradient $\Delta N/\Delta h$, expressed in km $^{-1}$ to study such phenomena.
In normal conditions $0 < \Delta N/\Delta h < -79$, the ray has as slightly greater radius of curvature than the Earth so it will reach a little beyond the optical horizon, as depicted in green in Figure 1. If $-79 < \Delta N/\Delta h < -157$, the ray will have a significantly greater radius, thus reaching considerable distances (red in Figure 1) before touching ground.

When $\Delta N/\Delta h = -157$, the ray has the same radius as the earth and will stay at the same distance above the ideal ground (red dotted line in Figure 1). If $\Delta N/\Delta h < -157$, the radius of the ray (in blue in Figure 1) is much smaller than that of the earth (in brown in Figure 1) and will soon reach it reflecting upwards, then reflect again on the atmospheric disturbed layer. This pattern is repeated a number of times reaching distances of thousands of kilometers in what is known as a tropospheric duct. This is not very frequent and happens more often in trajectories over water which has excellent reflectivity. If $\Delta N/\Delta h$ is positive, the ray will bend upwards (orange in Figure 1) and the radio horizon is shorter than the optical horizon.

Figure 2 shows $\Delta N/\Delta h$ versus $h$ from which the type of tropospheric propagation can easily be inferred.

Standard practice is to substitute the curved rays trajectories by straight lines, drawn over an earth with a modified radius multiplied by what is known as the K factor [8], were $K = 1/[1 + a*\Delta N/\Delta h]$ and $a$ is the true earth radius, 6371 km. In a normal atmosphere, $K = 4/3$ and the radio horizon is 1.33 greater than the optical horizon.

Reception when the line of sight is blocked can also happen when there is a sharp physical obstacle in the path that can diffract the radio waves in many directions, but the amount of energy in a particular direction will be heavily attenuated. The attenuation in dB introduced by a sharp object can be calculated [10] using:

$$f(v) = 6.9 + 20 \times \log(\sqrt{(v-1)^2 + 1 + v - 0.1})$$

where $v$ is a geometric parameter that depends on the wavelength, the height and the angles of view and distances from each end-point to the obstacle. Diffraction from round shaped obstacles is much less pronounced.

Even in a normal troposphere, dust, rain, snow or local inhomogeneities can change the trajectory of a radio signal so that it can reach well beyond the earth curvature in what is known as tropospheric scatter. Scattering occurs when the wave encounters objects whose dimensions are of the order of magnitude of the propagating wavelength. The energy will be radiated in many different directions as opposed to what happens in specular reflections.

### 3. LORAWAN AND THE THINGS NETWORK (TTN)

The LoRaWAN architecture [12] is composed of three elements: the end-nodes, the gateways and the servers. An end-node broadcasts data frames using the LoRaWAN protocol and any of the gateways is able to receive the packets. Gateways will blindly relay the data to a Network Server using any kind of IP connectivity. The Network Server examines a specific field in the frame to determine which application should a particular frame be sent to. Applications are hosted in an Application Server.

The wireless communication takes place through a single-hop link between the end-device and one or many gateways. In Europe [4] LoRa uses eight channels in the license-free radio frequency bands from 863 to 870 MHz. Maximum Equivalent Radiated Power (ERP) is 25mW (14 dBm) and the end-device transmit duty-cycle should be 0.1% or 1.0% per hour depending on the channel.

LoRa uses what is known as a "chirp" modulation [15], a technology developed for sonar and radar applications. It uses fixed amplitude linearly varying frequency signals that span the entire channel spectrum. The spreading factor (SF) represents the number of chips used to encode each bit of information independently on the adopted error correction scheme. LoRa in Europe operates with spreading factors from 7 to 12. SF7 is the shortest time on air, SF12 will be the longest. Each step up in spreading factor doubles the time on air to transmit the same amount of data. Longer time on air results in less data transmitted per unit of time. Each step up in SF correlates to about 2.5 dB (theoretically, 3 dB) so SF12 will provide the highest sensitivity corresponding to the capability of detecting a signal up to 20 dB lower than the noise plus interference.
level, provided that the signal is above the receiver’s sensitivity threshold.

The Things Network (TTN) is an initiative [7] to build a world-
wide open source infrastructure to facilitate a public Internet of
Things (IoT). TTN uses LoRaWAN to build IoT networks. LoRaWAN
provides low-bandwidth communications over long distances. In
typical applications IoT nodes send few bytes of data every few
minutes/hours over distances in the range of 1-10 kilometers. These
technical characteristics allow the use of cheap devices that can
operate for several years on a single battery. TTN operates by al-
lowing users to share the access to gateways, which play the role
of access points for LoRaWAN networks. As the amount of traffic
generated by nodes is very limited, users are willing to share the
access to their gateways and this allows the network to have a
greater coverage. The Things Network, being a free public commu-
nity LoRaWAN network, applies the fair use policy of restricting
uplink airtime to 30 seconds per day per node. There are now over
11,000 TTN gateways worldwide, in more than 100 cities. Figure 3
shows the distribution of gateways in Europe as an example. TTN
manages both the Network and the Application Servers for the end
nodes that are accordingly configured.

4 THE TROPPO PLATFORM
The main goal of the TROPPO platform [8] is to examine radio
trajectories from end-nodes to TTN Gateways to understand if
anomalous propagation has occurred.

We developed probes (TP: TropoProbes) which periodically send
data that can be received by any gateway in range. The same packet
of 4 bytes is sent using different SFs, ranging from 7 to 12. Since we
deployed the TPs we know their exact position and height above
ground. These devices have been added to a TTN application. The
physical devices are LoPy4 from Pycom [1], with an omnidirectional
antenna. The output power has been set to 14 dBm since we estimate
that the cable and connector losses compensate for the antenna
gain so the total equivalent radiated power (ERP) is 14 dBm.

As we want to monitor more devices than just the ones we
deployed, the platform is developed so that it can digest data coming
from other end nodes as well. For that, we need to access only the
metadata of the packets being sent in order to be able to add these
nodes to the TROPPO platform.

The packets are also received by TTN gateways that are deployed
by third parties. As the coordinates of the TTN gateways must
be provided when registering it in TTN, we can determine the
trajectory from a specific end-node to a given gateway.

The gateways forward all received frames to the TTN application
server attaching a sequence number, timestamp and the value of
the received signal strength indicator (RSSI). The information about
the trajectory and the path attenuation can be easily deducted. In
Figure 4 blue balloons are locations of a TPs, while red circles are
TTN gateways that have received packets from them.

Our web platform allows the visualization of trajectories, shows
the RSSI and SNR received over time, the SF distribution of received
packets and depicts the terrain profile between the TP and the TTN
gateway. Visualization can be done for data received in the last 1,
10 and 30 days and for all received data.

5 PRELIMINARY RESULTS
5.1 Trieste Tropo Probe
The first TP, shown in Figure 4B, has been placed on the roof of
the ICTP’s Marconi lab building in Trieste, Italy, at 72 meters ASL.
The packets have reached about 20 TTN gateways, including three
gateways owned by us that worked as baseline for packet reception.
The farthest gateway we could reach is near Cesena, in Central
Italy, at a distance of 235 km. This is indeed a case of anomalous
propagation since the earth’s curvature is completely blocking the line of sight (LOS) at this distance.

The gateway received a total of 18521 packets in a three months time frame (from December 2019 to March 2020). Figure 5 shows the time distribution of packets received by the Cesena gateway. Some days no packets were received since anomalous propagation depends on atmospheric conditions.

![Figure 5: Distribution of packets received by gateway in Cesena. Some days no packets were received since anomalous propagation depends on atmospheric conditions.](image)

The distribution of SF in Figure 6 shows that packets sent with SF 12, 11 and 10 have a higher chance of being received than the ones with lower SF, since the higher SFs allow for reception at lower SNR.

![Figure 6: The distribution of SF shows that packets sent with SF 12, 11 and 10 have a higher chance of being received than the ones with lower SF.](image)

5.2 Sardinia Anomalous Propagation

A LoRaWAN device has been placed in the “UTabarka” vineyards in the island of San Pietro, south Sardinia, by the iXem Labs [3] in the framework of a smart agriculture project. It is located at 50 meters ASL and at only 2 meters above ground. As this device has been designed for another application, it uses a fixed SF of 12. We are recycling the data sent for the purpose of analyzing the anomalous propagation.

The packets have reached three TTN gateways, one in Sardinia (the intended recipient, part of the same project) and two in Barcelona, Catalonia, at 573 and 584 km distance. Figure 4:C shows as a blue balloon the location of the probe. The two red circles are TTN gateways which received packets beyond the optical horizon.

One of the gateways in Barcelona has received 104 packets in a 1 month period (beginning of February 2020 to March 2020), while the second one has received only 3 packets in the same period.

Distribution of packets received by the gateway in Barcelona is depicted in Figure 7. Notice the clustering of packets on February 3 and 25, 2020 and their absence in the intervening days, confirming the weather dependence of anomalous propagation.

![Figure 7: Packet received in Barcelona. The absence of packets from February 4, 2020 to 25, is due to the weather dependence of the tropospheric duct.](image)

6 DISCRIMINATING THE TYPE OF TROPOSPHERIC PROPAGATION

When very long LoRa trajectories are mentioned, it is not always clear which kind of anomalous propagation is involved. While anecdotes about very long links are abundant [6], it is important to use tools such as the ones we developed to be able to correctly adjudicate the specific type of propagation. Let’s analyse the three cases described below.
6.1 Super-refraction

A radiosonde was launched on February 14 from the meteorological station in Rivolto, 63 km from the ICTP building. With its data we calculated the refractivity gradient, shown in Figure 8, evidencing that it reached \(-130 \text{ km}^{-1}\) at 0.6 km, thus confirming the presence of \textbf{super-refraction} a day in which we received packets in Cesena, as shown in Figure 5. Therefore a factor \(K = 5.85\) must be applied to the radius of the earth in this case.

![Figure 8: Refractivity gradient versus height at Rivolto Station. Values below \(-79 \text{ km}^{-1}\) confirm super-refraction in the link between ICTP and Cesena.](image)

Figure 8: Refractivity gradient versus height at Rivolto Station. Values below \(-79 \text{ km}^{-1}\) confirm super-refraction in the link between ICTP and Cesena.

6.2 Tropospheric duct

If we consider the long link from Sardinia to Catalonia, on February 3, 2020, 20 packets with SF 12 on a 125 kHz bandwidth were received at a Barcelona TTN gateway with RSSI spanning from -112 to -120 dB and SNR form -9.5 dB to -20.5 dB.

The same day a radiosonde was launched at Decimomannu Meteorological station, (50 km from Island of San Pietro), which recorded atmospheric pressure, temperature and relative humidity at different heights, data used to draw Figure 2. Notice that \(\Delta N/\Delta h\) reaches \(-350 \text{ km}^{-1}\) confirming that we are in presence of a \textbf{tropospheric duct}.

6.3 Diffraction

![Figure 10: Profile Gattinara Vezza at \(k = 4/3\). The sharp edge diffraction introduces an additional loss of 19 dB, but reception is still possible.](image)

Consider the TP shown in part A of Figure 4. The blue balloon is a sensor installed by iXem Labs in the framework of a smart agriculture project at Gattinara in the Piedmont region of Italy. The LoRaWAN signal reaches about 15 TTN gateways. The gateway at Vezza d’Alba received 5 packets on February 10, 2020, when the radiosonde data from the station at Cuneo (35 km away) evidenced normal refractivity as shown in the green trace of Figure 12. Yet the profile is blocked, so this is a case of diffraction by a sharp ridge, where the level of the received signal is calculated by adding to the free space loss an additional term to account for the diffraction loss [10], calculable using equation (2).

The parameter \(\nu\) is obtained from the formula on Figure 10. Applying this formula to the geometry of this link in normal refractivity conditions, \((k = 4/3)\) results in \(\nu = 1.65\). Entering this value in equation 2 results in a diffraction loss of 17 dB. Since the FSL at 868 MHz over 100 km is 131 dB, the total attenuation is 148 dB, so the calculated received signal is 14 - 148 = -134 dBm, easily detectable.

Cuneo is another gateway reached from the Gattinara probe, and its LOS is also blocked by a sharp ridge, but nevertheless packets were received on February 2, 2020. Repeating the calculation for the geometry of this link, shown in Figure 11, we get \(\nu = 4.81\). Entering this value in equation 2 we see an additional attenuation of 26 dB. Since the FSL over 140 km is 134 dB, the total attenuation is 160 dB, implying a received signal of -146 dB, below the receiver sensitivity. So, to explain the reception we used the data gathered by the radiosonde at Cuneo, 8 km away, to draw Figure 12. The red line corresponds to a day with no packet reception, the green line corresponds to another day where no packets were received. From the red line we can see a condition of super-refraction, with \(\Delta N/\Delta h =\)
-115 at 0.8 km. This corresponds to $K = 3.74$, and entering this value in BotRf we obtain the profile of Figure 11, in which the geometric parameter $\nu$ can be calculated as $2.07$. Entering this value in equation 2 produces a diffraction attenuation of 19 dB, so now the received level is $14 - (134 + 19) = -139$ dBm, which is indeed detectable. We conclude that there is a combination of diffraction and super-refraction in this case.

Figure 11: There is no line of sight between the probe in Gattinara and the TTN gateway in Cuneo. Diffraction combined with super-refraction is the mechanism involved.

Figure 12: Refractivity gradient versus height at Cuneo station. In green a day with no reception, where the gradient is negative and higher than $-79$ km$^{-1}$, in red when super-refraction allowed reception. After the gradient reached -115 km$^{-1}$ (at an elevation of 0.8 km) the wave bent downward and did not reach higher elevations.

7 FUTURE WORK
We intend to add more TPs in the near future. We would like to engage the TTN community to add more devices to the platform. Devices that are used for other purposes can be monitored by the TROPPO platform. In order to do so, we need access to the metadata of the data packets and not to the data payload itself. Please contact the corresponding author of this paper if you are interested in collaborating in such experiment.

8 CONCLUSIONS
We have presented a novel platform to obtain a great number of instances of anomalous propagation by leveraging the existing TTN gateways infrastructure. Deploying a few probes that periodically transmit short frames allows the detection of tropospheric propagation phenomena and also sheds light in the specific kind of anomalous propagation involved in each case, by leveraging meteorological publicly available data from radiosondes. We have developed a tool that automatically sorts out paths in which the line of sight is blocked, so that the propagation can only be accounted for by diffraction, super-refraction, tropospheric ducting or a combination of diffraction and super-refraction. Examples are provided of each of the four kinds, confirmed by meteorological data gathered at nearby stations. The TP hardware deployed is inexpensive and by leveraging the existing infrastructure of a great number of TTN gateways and public meteorological data, it can be easily scaled up by simply adding additional end-nodes.

ACKNOWLEDGMENTS
We would like to thank; Sebastian Buettrich and John Cassidy for the constructive discussions; CISAR Trieste for the kind support; TTN for the fantastic community they have created.

Data from the meteorological station were obtained from [9] of the University of Wyoming, curated by Larry Oolman to whom we express our gratitude.

REFERENCES
[1] Pycom Lopy 4. 2020. Pycom Lopy 4. https://pycom.io/product/lopy4/
[2] Les Barclay. 2003. Propagation of radio waves. Vol. 2. 1st ed.
[3] GP Colucci, M Poletti, Riccardo Stefanelli, and Daniele Tranchero. 2017. Internet of Things as a means to improve agricultural sustainability. In 2017 IEEE Biomedical Circuits and Systems Conference (BioCAS). IEEE, 1–4.
[4] Short Range Devices. 2017. Radio equipment to be used in the 25 MHz to 1 000 MHz frequency range with power levels ranging up to 500 mW. ETSI. Nice, France 220-1 (2017), 28–30.
[5] Imke Durre and Xungang Yin. 2011. 6B. 2 Enhancements of the data set of sounding parameters derived from the integrated global radiosonde archive. (2011).
[6] TTN Forum. 2020. TTN Long Link. https://www.thethingsnetwork.org/community/berlin/post/jobs-ttn-2019-in-zahlen-und-der-packet-broker-ist-da
[7] Wienke Giezeman. 2016. The things network: Building a global iot data network in 6 months. medium.com (2016).
[8] ICTP T/ICT4D Lab. 2020. TROPPO LoRa platform. http://wireless.ictp.it/tropo/
[9] University of Wyoming. 2020. Atmospheric Soundings. http://weather.uwyo.edu/upperair/sounding.html
[10] P Series. 2018. 526-14: Propagation by diffraction. Recommendation ITU-R P. tech. rep., ITU, Tech. Rep. ITU-R (2018).
[11] P Series. 2019. 310-10: Definitions of terms relating to propagation in non-ionized media. Recommendation, ITU-R P. tech. rep., ITU, Tech. Rep. ITU-R (2019).
[12] Nicolas Sornin, Miguel Luis, Thomas Eirich, Thorsten Kramp, and Olivier Hersent. 2015. Lorawan specification. LoRa alliance (2015).
[13] Lorenzo Vangelista, Andrea Zanella, and Michele Zorzi. 2015. Long-range IoT technologies: The dawn of LoRaâ€‘. In Future access enablers of ubiquitous and intelligent infrastructures. Springer, 51–58.
[14] Marco Zennaro, Marco Rainone, and Ermanno Pietrosemoli. 2016. Radio link planning made easy with a telegram bot. In International Conference on Smart Objects and Technologies for Social Good. Springer, 295–304.