Radio frequencies for the Internet of Things:
A new paradigm
for engineers

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Abstract:
The Internet of Things (IoT) is going to generalize the use of radio waves to connect devices of varied sorts: new uses but also new constraints. Short, infrequent messages emitted by millions of devices cannot be managed like downloads of videos or online gaming. The IoT forces us to rethink the assignment of bandwidths and adapt communication protocols. Sigfox network invented such an approach with its ultra narrowband technology, a paradigm that the cellular and satellite IoTs have taken into account. Since the radio-frequency spectrum necessary for the IoT is small in comparison with other uses, we can imagine that a bandwidth would be devoted to the IoT. Such a bandwidth, if harmonized worldwide, would be conducive to the emergence of global solutions for the Internet of Things.

The era of radio communications started in 1895 with Marconi's first experiments. More than a hundred years later, the cellular solutions used for billions of mobile telephones now prevail in the radio communications market. Initially designed for human-to-human (H2H) communications, cellular systems have come to serve human-to-machine (H2M) and then machine-to-machine (M2M) communications. Meanwhile, the Internet of Things (IoT) has emerged, extending the concept of connectivity to any device connected via radio waves.[1]

The many definitions of the IoT (MADAKAM *et al*. 2015) are centered on the problems of the network that has to route the data produced by connected devices. Herein, I prefer recentering this definition on the "things" themselves, since they impose the strongest constraints on the global system. The IoT represents the possibility of connecting to the Internet devices that we do not at all consider to be computers. A wheat field, a smoke detector, a water meter or a container to be shipped all fit under this definition of the Internet of Things.

A first remark is that a native source of electricity is missing in nearly all these connected devices. Batteries — indispensable to the IoT — have been a major drawback for radio communications. A few other characteristics of communications via the IoT are:

- BATTERY LIFE AND ITS PREDICTABILITY. For connected devices, a battery's life now lasts years (more than twelve for water meters) instead of days (as for mobile phones that are recharged when need be). Furthermore, the predictability and invariance of the battery's life, regardless of radio conditions, are conducive to the management of large numbers of connected devices.
- MESSAGES FOR APPLICATIONS ARE OF A VERY LIMITED SIZE. A few bytes suffice for detecting the GPS position, setting an index for counting or coding an alarm to signal a warning.
- MESSAGES ARE NOT SENT FREQUENTLY. The use of the IoT amounts to fewer than a hundred or so messages per day but to fewer than ten in the large majority of cases.
- THE ASYMMETRY OF DATA STREAMS. Most devices transmit many more messages toward the Internet (uplinks) than they receive from it (downlinks).

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[1] This article has been translated from French by Noal Mellott (Omaha Beach, France). The translation into English has, with the editor's approval, completed a few references. All websites were consulted in October 2020.

- THE HIGH DENSITY OF CONNECTED DEVICES. The density in urban areas can reach 50,000 or even a million connected devices per km^2 — far above the density of cellular phones. IoT solutions must, therefore, have a high degree of scalability (adaptability in size).

These characteristics differ significantly from those of cellular devices.

For nearly thirty years now, the search has been on for telephones with higher bit rates and a larger capacity per base station. Generation after generation, cellular technology is trying to make the best of the radio-frequency bands (made available by regulatory authorities) by tightly organizing how mobile phones use the radio-frequency spectrum (the timing and frequency of signals) and connect to base stations. This approach, which heavily relies on using the information carried by radio signals, does not suit the IoT. For the latter, efforts are being made, before all else, to reduce the energy needed for communications. The technical choices to be made for the IoT are, therefore, different with regard to the spectrum and communication protocols.

To address this new situation, Machina Research (2013) has worked out the concept of LPWAN, a low-power wide-area network. These LPWANs solve an apparent contradiction: long-range communications over wide areas but with a small number of base stations and low-power connected devices compatible with the use of batteries.

The choices of radio frequencies for the IoT

Designing a solution for connectivity to the IoT entails making three choices about: the regulatory framework, the optimal wave lengths and the quantity of radio frequencies necessary for the expected service.

The first choice has to do with the regulation of the frequencies to be used. The licensing of radio bands provides a generally favorable — predictable — environment on the spectrum. Interference is well known, generated by systems using familiar equipment. To its disadvantage, this solution entails the cost of the license, which might jeopardize the IoT's business model, since the unit cost of connectivity has to be significantly lower than for previous M2M systems. Another solution would be to use bands under a general authorization (thus without a license). The requirements related to sharing the spectrum (listed in Table 1) are set by regulatory authorities and usually harmonized by geographical area. They are always simple to implement and are based on a local decision about each objet that transmits messages. In other words, they do not call for coordination between devices. If these conditions were met, access to the authorized radio bands could be open for free. However this would, in turn, create an environment with a totally unpredictable level of interference.

Table 1: Requirements for sharing unlicensed sub-gigahertz radio-frequency bands

Geographical zone	*Band*	*Maximum power*	*Sharing techniques*
Europe	862-876 MHz	25 or 500 mW	transmission rate limited to 1% or 10% of the time
The Americas	902-928 MHz	1W	frequency hopping every 400 ms
Japan	920-923 MHz	20 or 250 mW	detection of occupation prior to transmission

The second choice: which wave lengths are to be devoted to the IoT? The UHF (300-3000 MHz) is of prime interest: the 800-1000 MHz band represents a sound choice balancing the size of antennas, path losses and the performance of chipset radio devices. The band without a license (2.4 GHz used for WiFi) is not suited for LPWAN on account of the high number of path losses. However this band is widely used for low-energy purposes, such as WiFi HaLow® and BlueTooth® Low Energy. This has been called the "proximity IoT".

The third choice: how much of the spectrum is needed for IoT connectivity? While the proximity IoT might benefit from the strong attenuation to 2.4 GHz in order to reuse frequencies in a given area, LPWANs cannot rely on this phenomenon to restrict their frequency needs. After all, they communicate over distances of several kilometers, even in dense urban areas. The solution comes from the communication profiles of connected devices on LPWAN: short, infrequent application messages from a very large number of devices can be satisfied with a few hundred kHz (ETSI 2017).

Current systems

Cellular

Before the idea took shape of connecting all objects via the Internet, cellular technology was already being used to connect machines. The first M2M systems used the circuit mode, but without much success. True M2M solutions emerged with the coming of GPRS (general packet radio service) at the turn of the millennium. This simple-to-use cellular technology relies on standard channels of 200 kHz in the 2G licenced bands. It is widely available in second-generation networks (or higher), but its maximum link budget (144dB) without antennas leaves many white spots in coverage. Machines installed in fixed places are thus hard to connect.

3GPP (3rd Generation Partnership Project) has recently proposed the NB-IoT (narrowband) and LTE-M for covering white spots for M2M communications. The increased link budgets of these solutions improve coverage, even in "difficult" places (dense urban environment, inside buildings). LTE-M fits into the frequence tables of LTE (the long-term evolution standard for wireless broadband communication) but requires that the connected device manage a 1.4 MHz band in order to establish communications, even if the volume of communications is low. NB-IoT uses dedicated channels of 200 kHz, which may be in either the 4G spectrum (in-band), the guard bands of LTE, or the 2G bands (stand alone).

LPWAN

For bands without a license, there is a strong limitation on the IoT's connectivity, namely: the power emitted, which, in Europe and depending on the frequency band, may be 25 or 500 mW. To have a long range of communication and limit the number of white spots, modulations have to be made when transmitting signals. Moreover, the signal has to be efficiently handled when received in order to have a large link budget despite the low power used for transmissions.

Semtech has opted for Lora, a long-range technology invented by the French company Cycleo. The transmitted signal undergoes CSS (Chirp Spread Spectrum) in a channel of 125 kHz. Upon reception, a specialized integrated circuit detects the signal by correlation, thus eliminating noise and random disturbances on the channel. A LPWAN CSS network uses several channels depending on the density of the messages to route.

Contrary to spectrum spread, Sigfox's 3D-UNB technology uses a random modulation by subcarrier on an "ultra" narrow band. This technique, similar to an unorthogonal OFDM, concentrates a signal's energy in a single subcarrier (a "quasi-tone") with a random central frequency. At the receiving station, each signal received passes through an adapted filtering system based on a high degree of dynamics and linearity. Since each quasi-tone occupies a space on the spectrum of a few hundred hertz, a very large number of quasi-tones can be transmitted simultaneously and received with a low probability of collision on a band of a few hundred kilohertz. Sigfox thus provides a service of connectivity for all of Europe with 2x200 kHz in the unlicensed frequencies (868-870 MHz).

Furthermore, 3D-UNB technology relies on a truly innovative method, also invented by Sigfox, for using the spectrum: "pervasive listening", which places the network of base stations at the service of connected objects. All base stations listen together on the same 200 kHz band. So, a device transmitting a message does not need to alert the station so that the latter receives its messages. The device only has to transmit its stream of data directly (without, we might say, sending an alert); and the data will be received by the station and, usually, by several stations. To its advantage, this multiple reception has a geographical spread conducive to the quality of the service. Pervasive listening, this new method for using the spectrum, is well adapted to handling the aforementioned problems related to the IoT. Devices may be very simple since they access radio frequencies on their own. All the complex tasks of managing random access and the interferences due to collisions are shifted toward the base stations and Sigfox's network.

Satellite

Communications by satellite are thought to be potentially accessible around the globe. The IoT by satellite follows this idea, in particular for use cases such as inter- or trans-continental logistics and the monitoring of connected objects in isolated areas. Compared with other systems of communication by satellite, the IoT imposes a heavy technical requirement: the low energy available and, therefore, the low power for uplinks to satellites. For example, a power of 25 mW allows for reception by a low-earth-orbit satellite (LEO), but not by a geostationary satellite. Given the current state of technology, an IoT service of connectivity by satellite will, therefore, necessitate a constellation of LEO satellites.

For uplinks, unlicensed frequencies or the frequencies already allocated to communications with satellites may be put to use. Reusing unlicensed frequency bands would ensure a continuity of service, since connected devices transmit data whether or not they are heard by base stations on the ground or by satellites in the constellation. For downlinks, the frequencies used must, under regulations, lie in the bands harmonized for satellites. The part of the UHF spectrum below 1 GHz represents, once again, a worthy compromise. The tough part of the problem with satellites is the IoT's capacity for managing a large stream of messages when satellites hover over dense zones.

The future?

For the very large majority of uses related to the IoT, the UHF frequencies close to a gigahertz are of interest for all techniques of connectivity being imagined, whether cellular, LPWAN or satellite. To their advantage, they strike a balanced compromise between path losses, the dimension of antennas, and the possibilities for using chips. Their main limitation is the absence of worldwide harmonization, — so, radio equipment has to be designed for each regulatory region.

Even if deployed on a vast scale, the IoT will only account for a small quantity of the data to be conveyed per surface unit. We can, therefore, imagine an eventual worldwide harmonization of the spectrum for IoT connectivity, since a few hundred kilohertz would suffice for a global service. The most important challenge will be to simplify access to the spectrum for devices that cannot be very complex but are to be connected to the IoT.

References

MADAKAM S., RAMASWAMY R. & TRIPATHI S. (2015) "Internet of Things (IoT): A literature review", *Journal of Computer and Communications*, 3, pp. 164-173, available at http://dx.doi.org/10.4236/jcc.2015.35021.

MACHINA RESEARCH (2013) "Revolution, evolution or distraction? View on emerging low-power wide-area wireless technologies in M2M", webinar on 3 June, available at https://machinaresearch.com/news/webinar-revolution-evolution-or-distraction-machina-researchs-view-on-emerging-low-power-wide-area-wireless-technologies-in-m2m.

ETSI (2017) "System reference document (SRdoc); short range devices (SRD); technical characteristics for Ultra Narrow Band (UNB) SRDs operating in the UHF spectrum below 1 GHz", ETSI TR 103 435 v1.1.1, February, 54p., available via https://www.etsi.org/deliver/etsi_tr/103400_103499/103435/01.01.01_60/tr_103435v010101p.pdf