Should we bother with the speed of light in everyday life? A closer look at GSM technology

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Should we bother with the speed of light in everyday life? A closer look at GSM technology

Tomasz Kawalec

Marian Smoluchowski Institute of Physics, Jagiellonian University, ulica Reymonta 4, 30-059 Krakow, Poland

E-mail: tomasz.kawalec@uj.edu.pl

Abstract

The speed of light, or more generally, the speed of electromagnetic waves, seems to be incredibly high. 300 000 km s^{-1} is far greater than the typical speed of a car, a plane or even a rocket, which is just several kilometres per second. It is thus natural that we treat the speed of light as infinite in everyday life. It appears, however, that even such a high but finite speed causes problems that have to be solved in one of the most popular electronic devices—cellular phones. Here we look more closely how the global system for mobile communications (GSM) phone works and how it deals with the speed of electromagnetic waves.

Introduction

Mobile phones seem to be an interesting tool for helping to teach physics, especially in the context of real life. The introduction of mobile phones to the teaching process of physics may follow several fruitful ideas, as described in [1–4]. On the other hand, the basics of wireless communication are worth a separate presentation—see e.g. [5] and [6]. Here we look more closely at the global system for mobile communications (GSM) mobile phone as a transmitter and discuss how the speed of electromagnetic (EM) waves—being for us incredibly high (close to 300 000 km s^{-1})—affects the most popular system of mobile telephony. The finite speed of EM waves forces the GSM system to be slightly more complicated and constitutes the fundamental limit of the cell radius. Interestingly, the finite speed of EM waves might also be an advantage and is directly used in global positioning systems (GPSs) [7]. It is worth noting that a rough measurement of the propagation delay of a light beam caused by a finite speed of light (being a kind of EM wave) is relatively easily accessible in a classroom.

Picking up mobile phone signals

GSM mobile phones transmit encrypted voice and text information, usually in the 900 or 1800 MHz bands, using Gaussian minimum shift keying (GMSK) modulation. This kind of modulation provides efficient use of the frequency range assigned for the radio transmission. The mobile phone communicates with the nearest base transceiver station (BTS) and then the signal is sent to the telecommunication network. The antennae of BTSs are easy to find on masts, chimneys or buildings.

First we try to find out what kind of signals a mobile phone generally transmits. We have to remember that it is important here to use

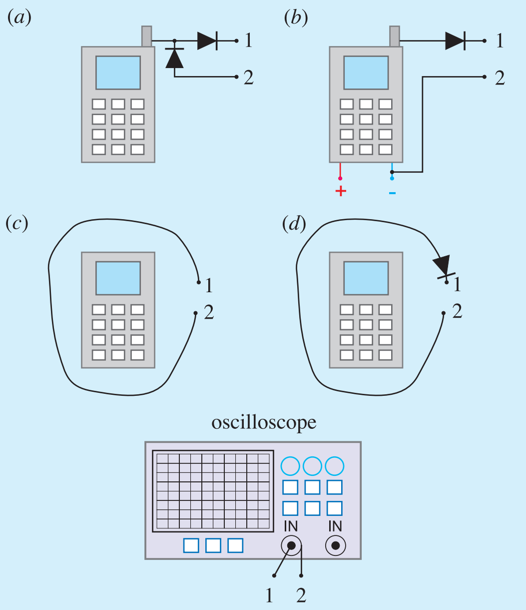

Figure 1. Different methods to capture the GSM mobile phone signal: (*a*) and (*b*) make use of an older phone with an external removable antenna. In (*b*) the minus of the battery is also used. In (*c*) and (*d*) a small loop is used, following the idea shown in [5]. The diode is recommended for slower oscilloscopes.

either a GSM (2G—second generation) phone or GSM/3G one but manually switched to GSM mode. There are several methods to pick up a mobile phone signal, as shown in figure 1. In (a) and (b) an older type of phone with an external removable antenna is used. The diodes together with the oscilloscope input impedance and capacitance are used to remove the ultrahigh frequency component so that we can conveniently observe only the envelope of the transmitted signal. In (a) the only modification of the phone is to remove the antenna and to connect a piece of wire instead using e.g. a proper screw. In (b) we have to connect one of the wires from the oscilloscope (the ground) to the minus of the battery. This method is the best regarding the signal strength. Methods (c) and (d) are based on [5] and do not require any phone modification. The only thing to prepare is a loop made of a 30 cm piece of wire. If we have access to a fast oscilloscope (at least 500 MHz nominal bandwidth) we can use version (c). In this case we may try to measure the frequency of the emitted signal as an additional exercise. For

Figure 2. Left: exemplary connections according to figure 1(a) or (b). The diodes are directly connected to a screw mounted instead of an external antenna. Right: connections following figure 1(d) or (c) if we remove the diode.

slower oscilloscopes and a more readable signal setup (d) is recommended. In figure 2 we see exemplary realizations of the schemes shown in figure 1. We have to remember to use a battery operated mobile phone. Otherwise the switching power supply connected to the phone generates excessive electromagnetic noise preventing signal observation on an oscilloscope.

To test our setup we dial a number we know nobody will answer and observe the signal on the oscilloscope. The time base should be set to 0.5 ms/div and the sensitivity should be found experimentally. The initial recommended range is 2–100 mV/div. Depending on the trigger setting in the oscilloscope we see either stationary or horizontally jumping, almost rectangular pulses. We have to look carefully at the screen immediately that the phone initializes the connection. Usually only the first signal bursts sent by the phone are of a relatively high power. Within a few seconds the BTS collects the information about the quality of the transmission and forces the mobile phone to reduce the power to the lowest usable level, thus making our observations more difficult.

GSM signal bursts

As we have learned above, the GSM mobile phone does not transmit continuously but instead sends short signal pulses. This is true both when establishing a connection and during a voice conversation. Let us look more closely now at what a mobile phone transmits. In figure 3 we see the pulses displayed on an old

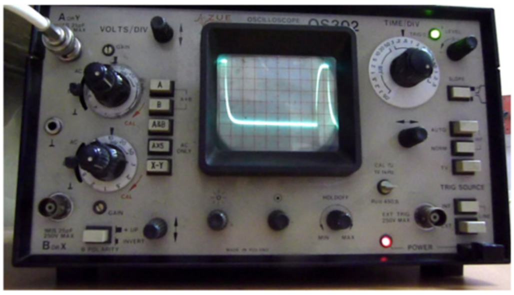

Figure 3. Signal bursts seen on an older type analogue oscilloscope. The time base was set to 0.5 ms/div and the sensitivity to 5 mV/div. The signal was amplified with the 5× option.

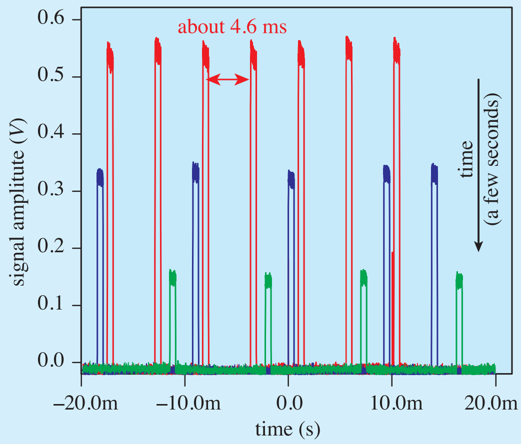

Figure 4. Three sets of bursts recorded with a digital oscilloscope connected as in figures 1(*a*), (*b*) and (*d*). Indeed, we see that a GSM mobile phone transmits in a pulsed mode. The pulses are separated by about 4.6 or 9.2 ms. The amplitude of the signal quickly drops with time—the BTS checks the quality of the transmission and forces the mobile phone to reduce its power to the lowest usable level.

type of analogue oscilloscope connected in the configuration shown in figure 1(d). We can check that the pulses appear every 4.6 or 9.2 ms (ms = 0.001 s).

The question arises, how it is possible to transmit a voice conversation without any breaks using a pulsed system? Firstly, our voice is converted with a microphone to an electrical signal which is digitized with an analogue-to-digital converter. The digital data are then loss compressed (based on the capabilities of human hearing) and divided into pieces consisting of e.g. 148 bits of information each. The subsequent pieces are sent inside the pulses we have just detected on an oscilloscope to the telecommunication network via BTS. On the other side, the data from the pulses are decompressed, connected together and transformed back to a continuous analogue signal. The final stage is to convert the analogue signal to sound waves using a speaker or earphones. The second question is: why use pulses of data instead of a much simpler continuous transmission? The reason is the necessity to provide as many simultaneous phone connections as possible using the radio bandwidth assigned to the GSM operator. One of the solutions is to share a single radio frequency between several users instead of only one. Such a system is called time division multiple access (TDMA) and is used to operate a few (eight or even sixteen in GSM) conversations using only one frequency channel. This is possible when each of the eight phones is forced to transmit periodically only in precisely defined moments called timeslots. The rest of the time (i.e. between timeslots) is left for the timeslots of other phones. This way the signals of different phones do not interfere.

In figure 4 we see three sets of signal bursts recorded with a digital oscilloscope. As we can see, as time passes the amplitude of the pulses drops significantly following instructions from the BTS, allowing the conservation of battery power in the mobile phone and reducing possible interference.

Now let us see how long a single pulse is. The upper graph in figure 5 shows a magnified single pulse recorded in a setup shown in figure 1(d) and the lower graph that in a setup from figure 1(c). In the first case we see only the envelope of the signal whereas in the latter the full signal is displayed and (after further magnification) we may try to measure its frequency. As we can see, the duration of the pulse is about 560 μs (i.e. a little bit more than half of a millisecond).

How does the speed of EM waves affect the GSM system?

As we know, each mobile phone may transmit only during a timeslot assigned by BTS. Let us assume now that we are close to the BTS and our phone transmits a burst of pulses. Since the

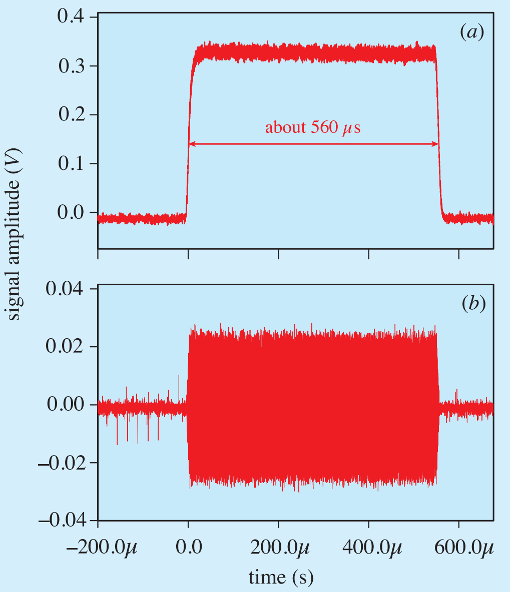

Figure 5. A single pulse recorded with a digital oscilloscope. The upper pulse was captured as in figure 4. The lower one was recorded using the simplest connections shown in figure 1(*c*), but with a high-speed (500 MHz) oscilloscope. The duration of a typical voice/data pulse is about 560 μs.

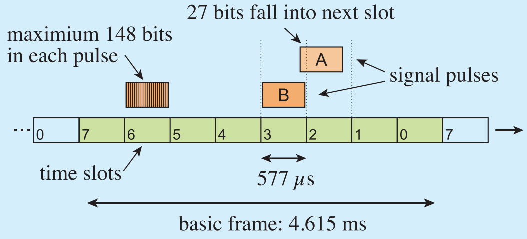

Figure 6. The pulse transmitted by a mobile phone must fit the corresponding time slot exactly to be properly decoded by BTS. Pulse A is sent 30 km from the BTS, but it takes 0.1 ms for the radio wave to reach the BTS. Pulse A misses its timeslot partially and is useless. Pulse B arrives on time—the mobile phone was told to transmit in advance to cancel the delay introduced by a finite speed of the electromagnetic waves.

distance to the BTS is small (let us say 100 m) the electromagnetic waves from our phone reach the BTS almost immediately (in about one third of a microsecond). But what happens if we are further away, for instance 30 km from the base station? It takes one tenth of a millisecond (0.1 ms = 100 μs) for the electromagnetic wave to travel to the BTS. Less than a millisecond seems to be a very short time, so how could it be significant? Let us look at figure 6. The greenish rectangle divided in eight pieces represents a set of consecutive timeslots for eight mobile phones. The whole set is called a basic frame and lasts 8 μs × 577 μs ≈ 4.6 ms. Each pulse sent by a mobile phone has to precisely fit its timeslot when it reaches the BTS. In the figure we see two pulses denoted by A and B, which should fit timeslots 2 and 3, respectively. Pulse A comes from a phone which is 30 km away from the BTS and misses its timeslot by 0.1 ms. This way about 27 bits out of 148 bits in a normal pulse of data are lost and the connection is terminated. Moreover, pulses A and B interfere partially. To circumvent this problem, the BTS calculates the delay introduced by the speed of EM waves for a given phone. Then it instructs the mobile phone to transmit a little bit in advance, so the pulses reach the BTS on time, as does pulse B. Due to other technical limits, the timing cannot be too far in advance. This way the maximal distance between the mobile phone and the BTS was chosen to be 35 km, which also gives the basic limit for a single cell radius. The timing advance signals are updated continuously to account for the changes in the position of the mobile phone user.

In reality, especially in cities, the cells are of a smaller diameter since the huge number of users requires the installation of a dense network of BTS stations to increase the capacity of a system. In the opposite case, in sparsely populated areas or near some islands, the maximal phone–BTS separation is extended thanks to an assignment of two subsequent timeslots to one mobile phone. This way the radio signal may travel further and the maximal distance can be as long as 120 km.

Although the speed of EM waves forms a basic limit for the GSM cell size, there is another important limiting factor—the relatively short range of the EM waves in the gigahertz band and the maximal radio power which may be used by a BTS and, more importantly, a mobile phone.

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T Kawalec is an assistant professor at the Faculty of Physics, Astronomy and Applied Computer Science of the Jagiellonian University in Krakow. His field of research is atomic physics, with an emphasis on cold atoms. One of his hobbies is modern radio communication systems.