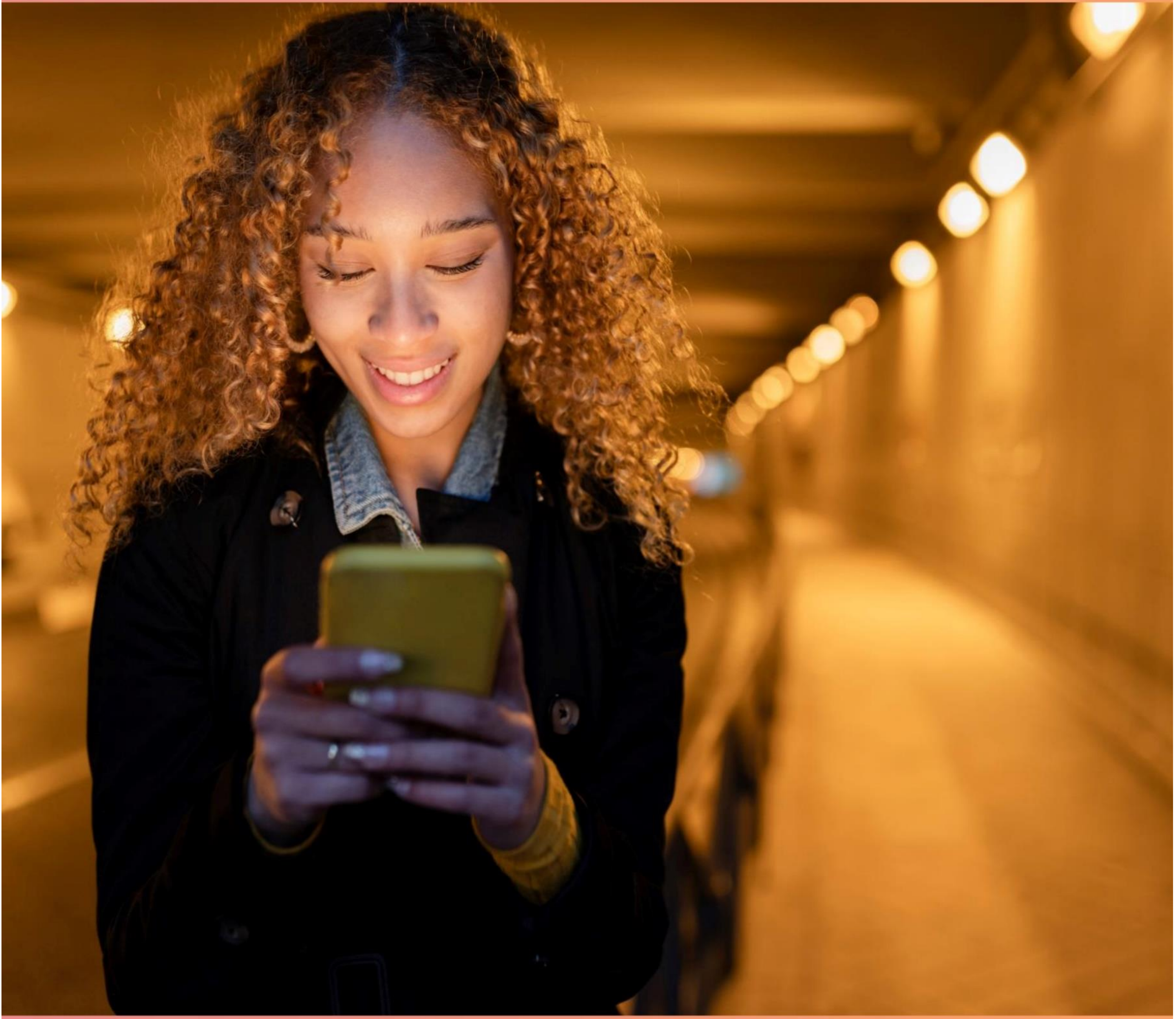
Resources for schools

Waves and mobile communication



NPL

UK Telecoms Lab

About UKTL

UKTL, the UK's telecoms security lab, provides a trusted, neutral space for operators and vendors to test security, resilience, and interoperability to support the diversification of its supply chain and enhance confidence in telecoms systems deployed in the UK. Based in the heart of the fast-growing West Midlands' tech hub in Solihull, it was established by the Department for Science, Innovation and Technology (DSIT) and is operated by the National Physical Laboratory (NPL).

UKTL helps vendors develop more secure products and identify vulnerabilities in already deployed equipment. UKTL's recommendations are not mandatory, but will speed up commercial decision-making processes, saving time and money. We monitor and identify opportunities through our expert Industry Advisory Board, as well as industry and regional engagement, and UKTL's own technical expertise and research.

UKTL brings together industry's best talent, to strengthen and enhance secure telecoms networks, playing a pivotal role in innovating and protecting the nation's infrastructure and growing skills in telecoms security.

Our work will help the UK to lead in open and interoperable networking, building UK expertise and supporting industry to deploy interoperable radio access network equipment across the networks. UKTL is committed to working in partnership, producing ground-breaking work, and providing reassurance for industry, government, academia, and the consumer.

Overview

The activities in this document allow learners to apply concepts from secondary science curricula in the context of telecommunications. In these activities, learners will:

- Identify the types of waves involved the process of making a mobile phone call and perform associated calculations, in **Activity 1**.
- Apply their knowledge of the properties of waves to determine the result of a given scenario involving the use of mobile phones, in **Activity 2**.
- Perform calculations relating to the use of satellite phones, in **Activity 3**.
- Explore the different electromagnetic waves used by a mobile phone and determine what makes microwaves suitable for mobile communication in **Activity 4**.

These activities can be used individually, or in series as part of a programme of learning. Model answers to the questions in each activity are given at the end of this document.

Activity 1: Waves and mobile phone calls

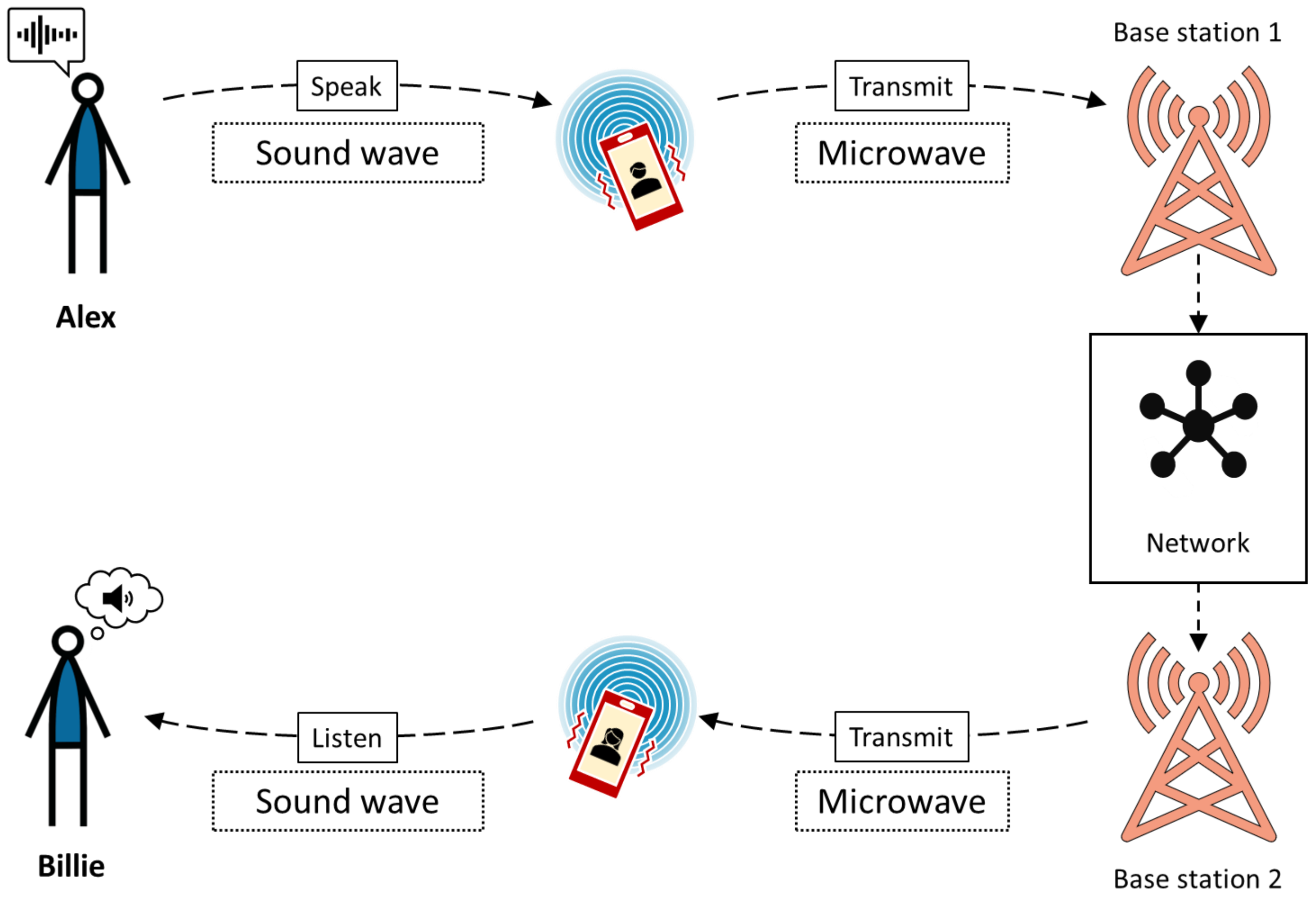
In this activity, we will examine the types of waves involved in the process of making a mobile phone call, and perform calculations on their speeds, frequencies and wavelengths. On the pages that follow, you will find three tasks:

- **Task 1: Longitudinal and transverse waves**, explores the types of waves involved in the process of making a mobile phone call.
- In **Task 2: Calculations on waves**, you will perform calculations to determine the wavelengths of the waves introduced in Task 1.
- **Task 3: Microphones**, explores how a MEMS microphone (the type of microphone found in mobile phones) works.

You will need to have a basic understanding of how mobile phone calls work before you attempt these tasks. The next section contains some information that will give you this understanding.

Background information

Over 10 billion phone calls are made across the world every day. Today, we take mobile communication for granted, but have you ever wondered how the sound of your voice reaches the person that you're speaking with when you make a mobile phone call? To answer this question, let's explore some of the key processes involved in a mobile phone call in the diagram below.



The steps outlined in the diagram on the previous page can be summarised as follows:

- **Step 1:** The microphone in Alex's mobile phone converts the sound wave produced by their voice into an electrical signal.
- **Step 2:** This electrical signal is encoded onto microwaves that are emitted by Alex's phone. These microwaves are not received by Billie's mobile phone directly but are instead received by nearest mobile phone base station (base station 1 in the diagram).
- **Step 3:** The base station passes the microwave frequency signal through the telephone network (a series of wires and optical fibres) to Billie's nearest base station (base station 2 in the diagram).
- **Step 4:** Base station 2 emits this signal as microwaves.
- **Step 5:** Billie's mobile phone receives this microwave signal and decodes it back to an electrical signal.
- **Step 6:** Finally, the speaker in the phone converts this electrical signal back into sound waves.

Our simplified approach

In reality, the process of making a phone call involves many more steps that those outlined above! The purpose of this section is to give you enough understanding to answer the tasks below, rather than a comprehensive overview of the entire process.

You many also have noticed that the diagram above assumes that the two phones have already been connected and the call has started, you do not need to understand how mobile phone calls are connected to complete the tasks below.

Task 1: Longitudinal and transverse waves

The process of making a mobile phone call involves both longitudinal and transverse waves. Use the diagram shown in the 'Background information' section above to answer the questions on the following page.

Assumed knowledge

We assume that you already know the difference between a longitudinal and a transverse wave – this task will consolidate that understanding. We also assume that you are comfortable expressing numbers in standard form, e.g. expressing 0.001 as 1×10^{-3}.

Questions

1. Which of the waves shown the in graphic is a **longitudinal** wave?

2. Which of the waves shown the in graphic is a **transverse** wave?

3. State the speed (through air) of the longitudinal waves in the graphic. If you do not already know, you can look it up.

4. State the speed of the transverse waves in the graphic.

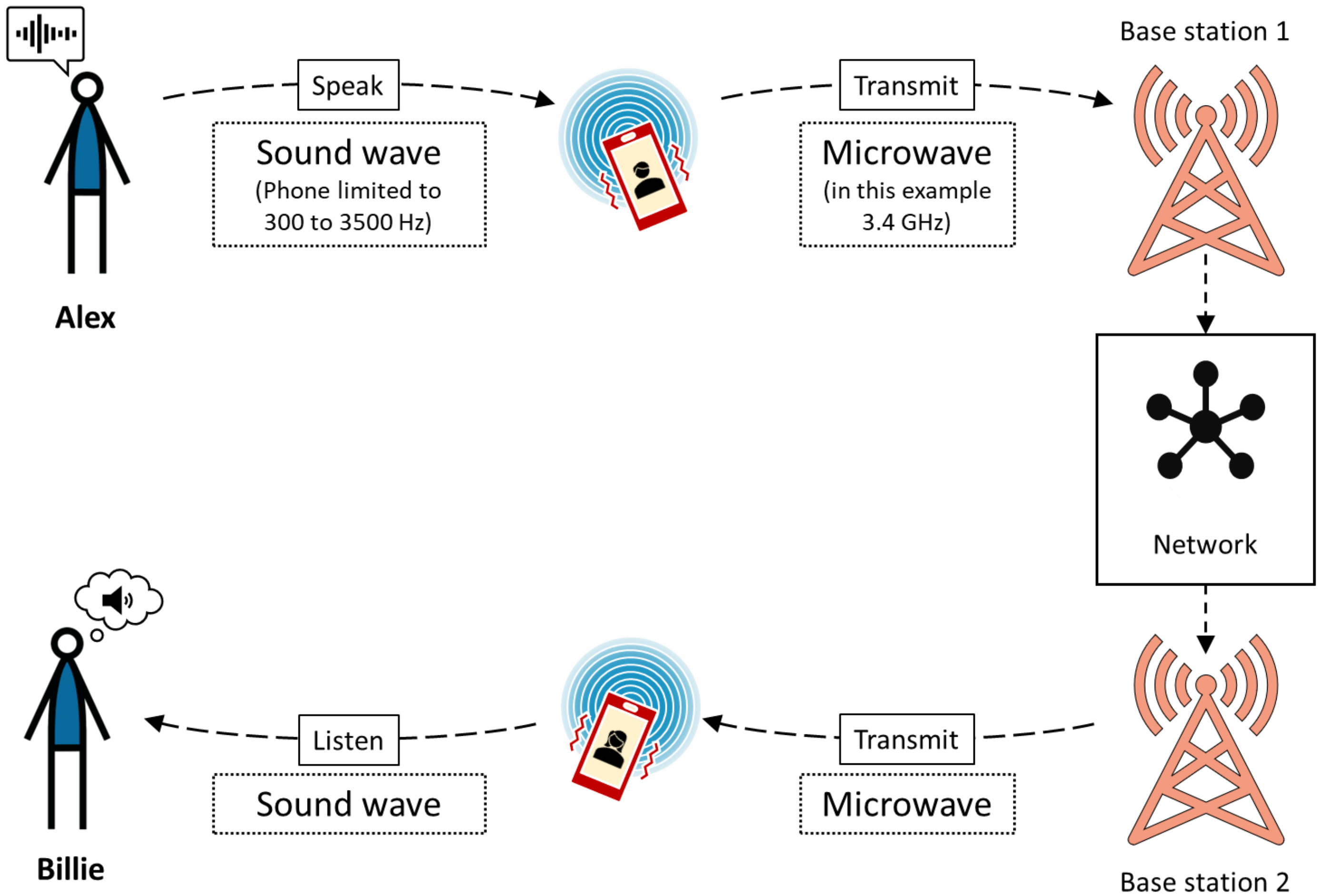
Task 2: Calculations on waves

The frequencies of some the waves involved in the process of making a mobile phone call are shown in the diagram below.

Use your answers to Task 1 and the equation:

$$wave\ speed = frequency \times wavelength$$

to answer the questions on the following page.



Remember that 1 GHz is equivalent to 1 $\times 10^9$ Hz

Questions

1. Calculate the wavelength of the microwave signal sent from Alex’s mobile phone to the base station, giving your answer in appropriate units.

2. Although humans can hear sounds with frequencies between around 20 Hz and 20 kHz, the audio frequency range used for mobile phone calls is much narrower. In this example, the audio frequency range of the mobile phone call is 300 Hz to 3500 Hz. Calculate the wavelength of the lowest and highest frequency of this range, giving your answers in appropriate units.

Lowest frequency:

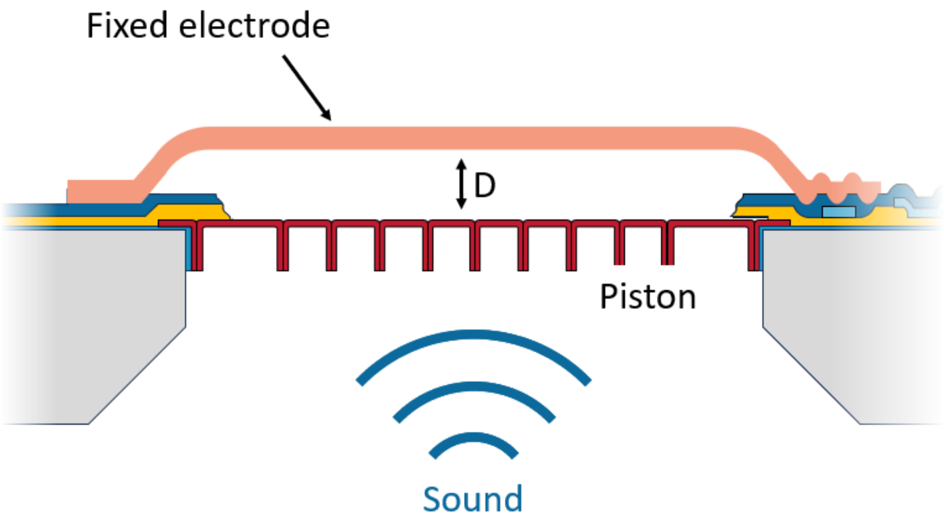
Highest frequency:

3. Compare the wavelengths that you have calculated in Questions 1 and 2 of this task.

Task 3: Microphones

The microphone in a mobile phone plays an important role in converting longitudinal waves (sound) into electrical signals that are then transmitted from the mobile phone as transverse waves (microwaves).

Mobile phones typically contain a MEMS microphone (MEMS stands for micro electromechanical systems). The diagram below shows an example of this type of microphone.



Use the diagram above to complete the activity on the next page.

Activity

Organise the phrases in the column on the left of the table below into the correct order to show how your mobile phone converts sound waves (which are longitudinal waves) into microwaves (which are transverse waves).

Jumbled up stage	Correct order
This pattern of this voltage change is then converted into a digital signal	
The piston vibrates	
The digital signal is encoded on to a microwave	
The sound wave (which is longitudinal) hits the piston	
Microwaves (which are transverse waves) are transmitted through the air	
This changes the distance between the pistons and the electrode (marked 'D')	
The distance change produces a change in voltage between the fixed electrode and the piston	

Activity 2: Phone calls and the speed of sound

Alex and Billie are speaking to each other on their mobile phones. During the conversation, they realise that they are both walking in the same park and can see each other.

Alex wonders:

- If I shout ‘Hello!’ as loud as I can, what would Billie hear first – the sound wave travelling across the park, or the sound of my voice coming through their mobile phone?

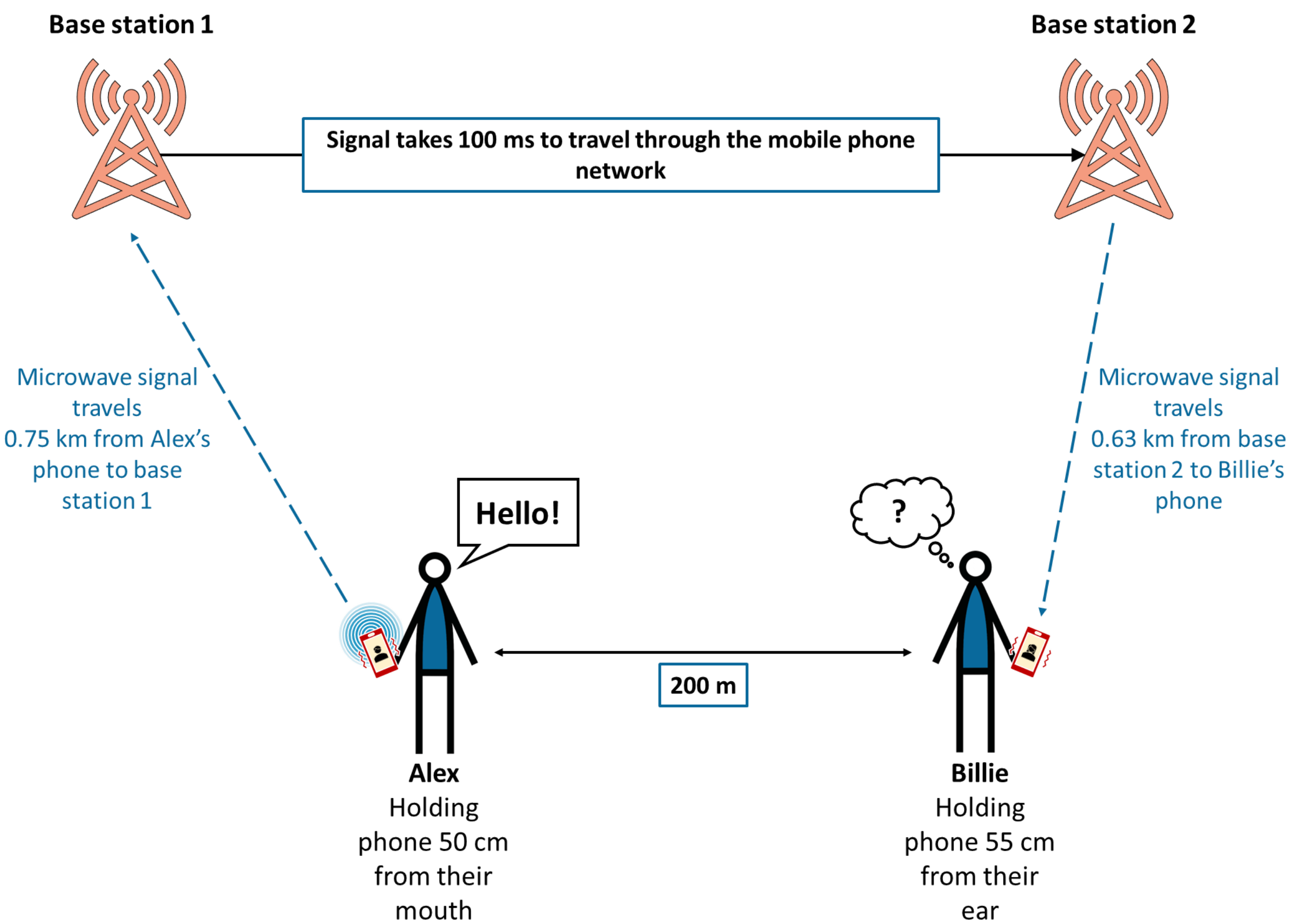
In this activity, we will perform some calculations to answer this question based on the information given in the section below.

The scenario

For the purposes of this task, let’s assume that Alex and Billie are 200 m apart when Alex shouts ‘Hello!’. Let’s also assume that:

- They are both using speakerphone, with Alex holding their phone 50 cm from their mouth and Billie holding the phone 55 cm from their ear
- Alex is 0.75 kilometres from the nearest mobile phone base station (base station 1)
- Billie is 0.63 kilometres from the nearest mobile phone base station (base station 2)
- It takes 100 ms (0.1 s) for the mobile phone signal to travel from base station 1 to base station 2 through the mobile phone network – this is the latency of the network
- The processing of the signal that happens within the two mobile phone takes zero time

This scenario is summarised in the diagram below.



Use the information presented in the diagram to answer the questions on the following page.

Questions

1. Calculate the time that it would take for the sound wave produced by Alex's voice travelling across the park to be heard by Billie, giving your answer to three significant figures.

2. Calculate the time that it would take for the sound wave produced by Alex's voice to reach their mobile phone, giving your answer to three significant figures.

3. Calculate the time that it would take for the soundwave produced by Billie's mobile phone speaker to reach Billies ear, giving your answer to three significant figures.

4. Calculate how long it would take for the transmission sent from Alex's mobile phone to reach base station 1.

5. Calculate how long it would take for the transmission sent from base station 2 to reach Billie's mobile phone.

6. Use your answers to Question 2 to calculate the total time taken for Billie to hear Alex's voice through the mobile phone. Give you answer to 3 significant figures.

7. Based on your answers above, what would Billie hear first — the soundwave travelling across the park, or the sound of Alex's voice coming through their mobile phone?

8. Using the answers to the questions above, comment on which step of the process in this scenario makes the most significant contribution to the delay on Alex and Billie's mobile phone call.

Activity 3: Satellite phones

Although the mobile phone network covers large parts of the UK, there are locations at which there is no mobile phone signal. In these locations, it is not possible to make a mobile phone call. However, a call could be made from such locations using a satellite phone.

Unlike conventional mobile phones, satellite phones do not transmit signals to a terrestrial base station, but instead send signals to satellites orbiting the Earth. These satellites relay signals back to Earth, where they are directed to the receiving device (e.g. a mobile phone).

Satellite phones typically send signals to one of two types of satellite:

- Satellites in geostationary orbit, which are approximately 35,700 km above the Earth
- Satellites in Low Earth Orbit (LEO), which are approximately 700-1000 km above the Earth

Use this information to answer the questions below.

Questions

1. Alex, who is in a remote location with no mobile phone signal, makes a satellite phone call to Billie's mobile phone. The satellite phone that Alex uses communicates with a satellite that is in low Earth orbit, 700 km above the Earth's surface. Upon receiving the signal, the satellite amplifies it and transmits it to a ground station back on Earth.

   Use the equation $speed = \frac{distance}{time}$ to calculate how long it would take the microwave signal sent by Alex's phone to reach the ground station.

   Note: You can assume here that the satellite amplifies and emits the return signal instantaneously. This isn't really the case, but we will make this assumption here to simplify the calculation. You might like to think about what other assumptions you make when answering this question and note them in the box below, along with your answer.

2. Imagine that Alex had made the call using a satellite phone that communicates with a satellite in geosynchronous orbit, 35,700 km from the Earth's surface. How long would the signal from Alex's phone take to reach the ground station in this case (assuming again that the satellite amplifies and emits the return signal instantaneously)?

3. Upon receiving the signal from the satellite, the ground station converts the microwave signal back into electrical signal, which is passed through a wired telephone network to a mobile base station that is 0.6 km away from Billie. This process takes 100 ms. The base station converts this electrical signal back into microwaves that are received by Billie's mobile phone.

   Calculate the time that the signal takes to travel from the ground station to Billie's phone.

4. Use your answers to Questions 1–3 above to calculate the total time taken for the signal sent from Alex's phone to reach Billie's phone if:

   a. Alex uses a satellite phone that communicates with a satellite in Low Earth Orbit, 700 km from the Earth's surface
   b. Alex uses a satellite phone that communicates with a satellite in geosynchronous orbit, 35,700 km from the Earth's surface

a.

b.

5. A delay of greater than approximately 200 ms on a phone call is noticeable, and can make conversations feel unnatural. Would you expect Alex and Billie to experience a noticeable delay on their phone call in the two scenarios outlined in Question 4?

Activity 4: Mobile phones and the electromagnetic spectrum

Task 1: Wavelengths produced by your phone

Your mobile phone emits and receives a variety of waves from certain regions of the electromagnetic spectrum. The table on the next page lists a number of examples of activities you can carry out with your phone and a typical wavelength associated with that application.

In this task, your job is to:

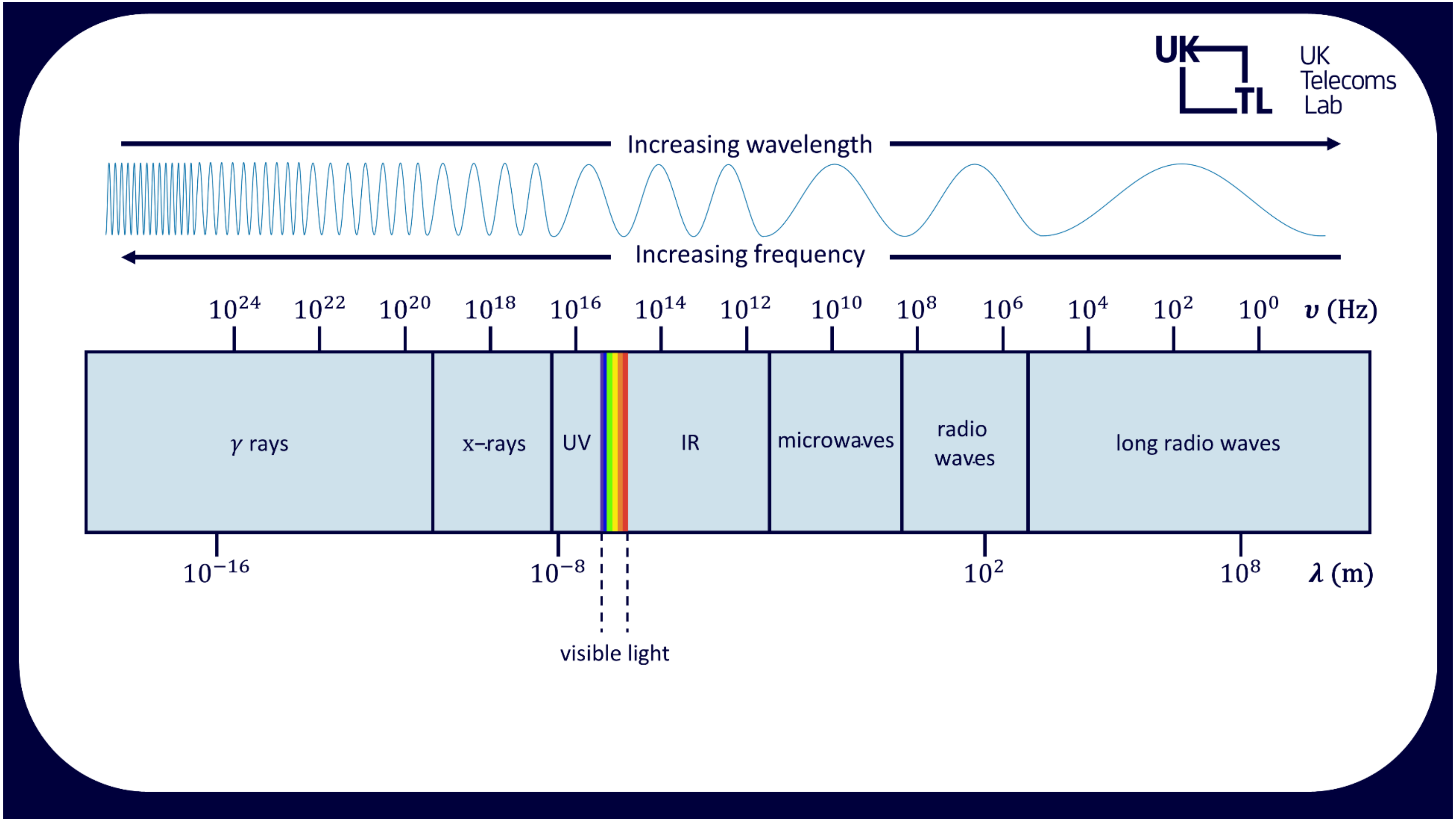
- Calculate the frequency of each of the wavelengths given in the table on the next page, and then…
- Use the diagram provided to determine in which region of the electromagnetic spectrum that wavelength falls.

Note that the numbers given in the table on the next page are illustrative examples and will vary between network provider and mobile service (i.e., 2G, 3G, 4G or 5G). Remember, the speed of light is 3×10^8 m s^{-1}. You may also find this table of SI prefixes useful:

Prefix	Name (Symbol)	Scientific notation
1 000 000 000 000	tera (T)	10^{12}
1 000 000 000	giga (G)	10^{9}
1 000 000	mega (M)	10^{6}
1 000	kilo (k)	10^{3}
1		10^{0}
0.01	centi (c)	10^{-2}
0.001	milli (m)	10^{-3}
0.000 001	micro (µ)	10^{-6}
0.000 000 0001	nano (n)	10^{-9}

Application	Approximate wavelength(s) used	Frequency	Region of EM spectrum
Making a 5G phone call	9 cm		
WiFi	12 cm or 6 cm		
Display/screen	447 – 500 nm		
GPS	20 – 27 cm		
Bluetooth	12 cm		
Sending a text message	30 cm		

Once you have filled in the table above, mark the wavelengths that you have calculated on the electromagnetic spectrum on the next page.


UK TL
UK Telecoms Lab
Increasing wavelength
Increasing frequency
10^{24} 10^{22} 10^{20} 10^{18} 10^{16} 10^{14} 10^{12} 10^{10} 10^{8} 10^{6} 10^{4} 10^{2} 10^{0} υ (Hz)
γ rays
x-rays
UV
IR
microwaves
radio waves
long radio waves
10^{-16} 10^{-8} 10^{2} 10^{8} λ (m)
visible light

Task 2: What makes microwaves suitable for mobile communication?

Now you have seen which wavelengths and frequencies are produced by your mobile phone, and what applications these are used for, have a go at the task below to understand the properties of microwaves that make them suitable for mobile communication.

For each property on the left-hand side, there is a corresponding advantage on the right-hand side. Your task is to match each property with the correct advantage.

Property
Microwaves are a form of non-ionising radiation…
Microwaves are not easily absorbed by solid materials…
Microwaves are not adversely affected by environmental conditions…
Microwaves are not absorbed by the Earth's atmosphere…
Microwaves are much higher frequency than other radio waves…

Advantage
…so have the ability to pass through walls.
…so heavy rain, snow, fog and sleet don't have an impact on broadband microwave transmissions.
…so pose minimal health risks to the public.
…so they support higher data rates and can be used to quickly transmit large amounts of information.
… so can be used for terrestrial communication or to communicate with satellites in space (e.g., for GPS applications or satellite phone calls).

Model answers

Activity 1: Task 1

1. Sound wave
2. Microwave
3. The speed of sound in air is approximately 340 m s^{-1}
4. Microwaves are electromagnetic waves and therefore travel at the speed of light, 3 x 10^8 m s^{-1}

Activity 1: Task 2

1. $\frac{3\times10^{8}\ \mathrm{m\ s^{-1}}}{3.4\times10^{9}\mathrm{Hz}} = 0.088\ \mathrm{m\ (to\ 2\ s.f.)}$
2. Lowest frequency: $\frac{340\ \mathrm{m\ s^{-1}}}{300\ \mathrm{Hz}} = 1.1\ \mathrm{m\ (to\ 2\ s.f.)}$

   Highest frequency: $\frac{340\ \mathrm{m\ s^{-1}}}{3500\ \mathrm{Hz}} = 0.097\ \mathrm{m\ (to\ 2\ s.f.)}$

3. The highest frequency longitudinal (sound) waves used for mobile phone calls in this example have a similar wavelength to the transverse waves (microwaves) that the phone uses to communicate with the base station.

Activity 1: Task 3

The correct order is shown below.

Correct order
The sound wave (which is longitudinal) hits the piston
The piston vibrates
This changes the distance between the pistons and the electrode (marked 'D')
The distance change produces a change in voltage between the fixed electrode and the piston
This pattern of this voltage change is then converted into a digital signal
The digital signal is encoded on to a microwave
Microwaves (which are transverse waves) are transmitted through the air

Activity 2

1. $t = \frac{200\ m}{340\ \mathrm{m\ s^{-1}}} = 0.588\ \mathrm{s\ (to\ 3\ s.f.)}$

2. $t = \frac{0.5\ \mathrm{m}}{340\ \mathrm{m\ s^{-1}}} = 0.00147\ \mathrm{s\ (to\ 3\ s.f.)\ or\ } 1.47 \times 10^{-3}\ \mathrm{s}$

3. $t = \frac{0.55\ \mathrm{m}}{340\ \mathrm{m\ s^{-1}}} = 0.00162\ \mathrm{s\ (to\ 3\ s.f.)\ or\ } 1.62 \times 10^{-3}\ \mathrm{s}$

4. $t = \frac{750\ \mathrm{m}}{3\times10^{8}\ \mathrm{m\ s^{-1}}} = 2.5 \times 10^{-6}\ \mathrm{s}$

5. $t = \frac{630\ \mathrm{m}}{3\times10^{8}\ \mathrm{m\ s^{-1}}} = 2.1 \times 10^{-6}\ \mathrm{s}$

6. $1.47 \times 10^{-3}\ \mathrm{s} + 2.5 \times 10^{-6}\ \mathrm{s} + 0.1\ \mathrm{s} + 2.1 \times 10^{-6}\mathrm{s} + 1.62 \times 10^{-3}\ \mathrm{s} = 0.103\ \mathrm{s\ (to\ 3\ s.f.)}$

7. Alex's voice coming through the mobile phone.

8. In this scenario, the time taken for the mobile phone signal to travel from base station 1 to base station 2 through the mobile phone network is the most significant contribution. In comparison, the times taken for the soundwaves and electromagnetic waves to travel are very small.

Activity 3

1. $t = \frac{1.4\times10^{6}\ \mathrm{m}}{3\times10^{8}\ \mathrm{m\ s^{-1}}} = 4.667 \times 10^{-3}\ \mathrm{s}$

2. $t = \frac{7.14\times10^{7}\ \mathrm{m}}{3\times10^{8}\ \mathrm{m\ s^{-1}}} = 0.238\ \mathrm{s}$

3. $t = 0.1\ \mathrm{s} + \left(\frac{600\ \mathrm{m}}{3\times10^{8}\ \mathrm{m\ s^{-1}}}\right) = 0.100002\ \mathrm{s}$

4. (a) $t = 4.667 \times 10^{-3}\ \mathrm{s} + 0.100002\ \mathrm{s} = 0.105\ \mathrm{s\ (to\ 3\ s.f.)\ or\ 105\ ms}$

   (b) $0.238\ \mathrm{s} + 0.100002\ \mathrm{s} = 0.338\ \mathrm{s\ (to\ 3\ s.f.)}$ or 338 ms

5. Based on the answers to Q4, in this scenario a noticeable delay would be expected on the call made using the satellite phone that communicates with a satellite in geosynchronous orbit.

Activity 4: Task 1

Application	Approximate wavelength(s) used	Frequency	Region of EM spectrum
Making a 5G phone call	9 cm	3400 MHz	Microwave
WiFi	12 cm or 6 cm	2400 MHz or 5000 MHz	Microwave
Display/screen	447 – 500 nm	600 – 670 THz	Visible light (blue)
GPS	20 – 27 cm	1100 – 1500 MHz	Microwave
Bluetooth	12 cm	2400 MHz	Microwave
Sending a text message	30 cm	1000 MHz	Microwave

Activity 4: Task 2

Property
Microwaves are a form of non-ionising radiation…**(a)**
Microwaves are not easily absorbed by solid materials…**(b)**
Microwaves are not adversely affected by environmental conditions…**(c)**
Microwaves are not absorbed by the Earth's atmosphere…**(d)**
Microwaves are much higher frequency than other radio waves…**(e)**

Advantage
…so have the ability to pass through walls. **(b)**
…so heavy rain, snow, fog and sleet don't have an impact on broadband microwave transmissions. **(c)**
…so pose minimal health risks to the public. **(a)**
…so they support higher data rates and can be used to quickly transmit large amounts of information. **(e)**
… so can be used for terrestrial communication or to communicate with satellites in space (e.g., for GPS applications or satellite phone calls). **(d)**