A Novel Platform to Teach Wireless Communication to Children and Teenagers

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Abstract

Every day, we are surrounded by billions of invisible bits transmitted by our phones, tablets, and laptops. Wireless communication is pervasive but hard to teach because radio waves (5G, WiFi, BLE) cannot be seen, and a sensory experience is key to learning. From a physics perspective, *radio* and *light waves* are similar, but our eyes only see light. Thus, we design a platform to teach the complex concept of wireless communication using *light*. With our platform, children can "see" how a device transmits information using a normal flashlight. Our design includes connections with robots, superheroes, and games to make a joyful learning experience. The platform was used by hundreds of school students at an international science fair. After a guided activity, 80% of the students reported understanding the basic idea of wireless communication and some students even identified advanced concepts, such as *interference*, playing on their own.

CCS Concepts

• **Applied computing** → *Interactive learning environments*; • **Human-centered computing** → *Interaction devices*; • **Social and professional topics** → *Children*.

Keywords

interactive learning, wireless communications, flashlight, educational robots.

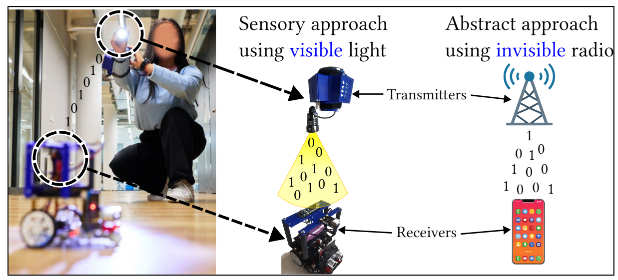

Figure 1: *T-light* is designed to teach the abstract concept of wireless communication to young students.

1 Introduction

Wireless communication is popular and pervasive. Every day we are surrounded by invisible flows of information carrying the data we exchange. However, if we would ask an average person to explain how phones transmit information over the air, very likely, the person would not know. Wireless communication is a fundamental pillar of society, but its knowledge is mainly reserved for a small fraction of students who enroll in engineering programs. Teaching the basics of this technology in schools could not only enhance the learning experience of STEM topics in children, but it could also help future citizens understand how technologies such as 5G, WiFi and BLE enable the operation of our toys, phones and watches. This understanding can help remove fears and misleading information about this pervasive technology. For example, in 2020, the United Kingdom had more than 100 incidents where people burnt down cell towers due to a conspiracy theory that *"links the spread of the coronavirus to an ultrafast **wireless technology** known as 5G"* [29].

Considering the significant role that wireless communication plays in our lives, we pose the following research question: *how can we teach the basics of wireless technology to students at different school levels (ages 5 to 17)?*

A major limitation in teaching wireless transmissions is that the concept is abstract. *Radio waves* cannot be seen, heard, or felt; and sensory experiences are fundamental to learning [3, 32]. To overcome this obstacle, we build upon the area of visible light communication to design a playful platform. The basics of wireless communication with light are simple: the process is similar to communicating with somebody by turning a flashlight on and off to send a Morse code [20]. Wireless communication with light has properties similar to 5G, BLE, and WiFi, but the unique advantage of using light is that students are able to **see** the actual transmissions. This sensory experience would allow students to uncover the "magic" of wireless communication enabling them to see how information flows over the air.

We present *Talking With Light*, *T-light* for short, an educational tool for children, teenagers, and even adults, to learn wireless communication. The platform consists of an armband with a *special* flashlight that sends wireless commands to a robot. *T-light*'s design was part of a supranational effort that matched teachers and researchers from different countries to teach advanced concepts in

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elementary and high schools. This approach enriched the design process, allowing us to include important principles to make the learning experience joyful: a sensory experience [25, 26], the use of robots [1, 6], a connection with superheroes [5, 11, 19, 27], and gaming [4, 18, 24].

The final prototype was presented at a large international science fair that was attended by more than 4,000 school students between the ages of five and eighteen. Several hundred children and teenagers utilized our platform and many of them (298) filled up the survey. The results were encouraging in terms of joy and education. The majority of children (80%) understood the basic idea of communication with light. The younger children were particularly happy, giving high-fives or hugs to our team after playing with the platform. Our booth had a word-of-mouth effect, some students called their friends to try our platform (*"The robot moves only when it is under this **special** light!"*). Some children even identified advanced topics in wireless communication, such as *interference*, without us having explicit activities to do so. Overall, we observed that the platform fostered the curiosity of children and teenagers on wireless communication.

2 Related Work

This section discusses prior teaching strategies in wireless communication, the importance of sensory learning, and STEM teaching methods with a focus on young students.

2.1 Teaching wireless communication

Formal education in wireless communication usually starts at college and it requires prior knowledge of electromagnetism, abstract mathematical concepts, and specialized equipment for laboratories [10, 31, 33]. That advanced curriculum, however, is only required to design a fully functioning radio system. Efforts to teach wireless communications in high schools include audio transmissions to "hear" the waves and oscilloscopes to display wave amplitude and frequency [8, 28]. These methods are suitable for motivated high school seniors but require expensive equipment and skilled staff. Moreover, oscilloscopes lack direct sensory engagement, making them less appealing to most students. On the other hand, Disney Research has used visible light communication to design new (i) *toy cars*, where automobiles from the movie Cars talk to each other through their headlights; and (ii) *magic wands*, where the tip of the wand is a light that "casts a spell" to a dress that changes colors based on the message sent by the wand [30]. Disney Research's light-based toys engage children but focus on entertainment rather than teaching wireless communication.

Our motivation to use light stems from its historical role in wireless communication, such as fire towers, lighthouses, and heliographs [20]. Light is more intuitive and easier to grasp than invisible radio waves. Using light to teach wireless communication goes back to the basics. Furthermore, light has the advantage of being an *electromagnetic wave* and this means that we can do with light (almost) everything that we can do with radio.

2.2 Sensory & tangible learning

Our work is related to, and inspired by, the areas of sensory and tangible learning. These methods have been applied in schools to teach various topics, like astronomy [25] and biology [26]. A notable example is *BodyVis*, which allows students from 6 to 12 years old to see and touch internal organs that are otherwise inaccessible to them.

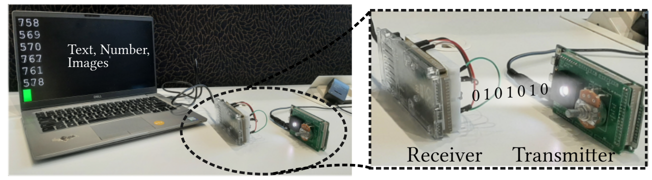


Figure 2: *T-light*'s first prototype. A beam of light transmits information (text or images) shown on a screen

There have also been non-educational efforts to "see" WiFi signals. One of those projects uses a robot with an antenna to measure WiFi signals at any given environment, and then, plots the signals as a picture [14]. A few artists have taken this method to create novel illustrations for decoration [21]. For example, one such illustration shows a picture of the White House, where one can see not only the sky, sun, and clouds but also a superimposed color barrage capturing the WiFi signals present in the air. We take inspiration from those projects, and the area of sensory learning, to design a learning platform to teach wireless technology to children.

2.3 STEM education and the role of heroes

Due to the engagement associated with heroes, their characters have been used as learning tools in classrooms [19, 27]. The connection between heroes and science has such synergy that in 2007 Marvel Comics launched an educational exhibit where they connected many of their characters to various scientific and engineering principles [27]. We take inspiration from these educational concepts to improve child engagement during our design process: We introduce wireless communication as a superhero power, where a Marvel character that radiates powerful beams of light (Iron Man), adds wireless communication to those light beams.

3 Design Process

Our design process is centered on child engagement. We included the input of a teacher, young adults, and children. In this section, we present first our design goals, and then our design process until the final platform is developed.

3.1 Design goals

The aim of *T-light* is *to teach the basic principle of wireless communication to school students using a **sensory approach.*** To achieve this aim, we considered three high-level design goals inspired by the related work. The first goal is a positive user experience. The process should be fun and enjoyable, which motivated us to design a system based on robots and superheroes. The second goal is to build upon a proven educational tool. The teacher in our team showed us what type of robot is already used widely in a school system, allowing us to build our design on top of that tool. The third goal is to enable self-discovery. The system should be lightweight and safe to allow students to discover further properties of wireless communication by themselves.

3.2 Initial idea: a sensory approach

The motivation to develop *T-light* came from an event organized by a supranational body. The event's goal is to motivate researchers to create platforms and methods to teach advanced topics to school students. The target audience is students from elementary and high school between the ages of five and seventeen years old.

Our first prototype consisted of a light (transmitter) and a photosensor (receiver), as shown in Figure 2. This basic prototype was inspired by the research area of Visible Light Communication (VLC), which is highly active [23] and allows transforming standard LEDs into wireless transmitters. *Our contribution is not on VLC, but on its educational potential.*

Our transmitter uses digital encoding transmitting ones and zeroes represented by the states of light ON and OFF, respectively. While using encoding is not close to the concept of modulation, it enables a simpler and more intuitive concept for younger pupils to understand that information is embedded in the light, directly associating 1s with light ON and 0s with light OFF. Our design uses Manchester encoding, which is widely used in several VLC works [9, 16, 22, 35]. Manchester encoding avoids long trails of high or low levels when there is a long trail of 1s or 0, maintaining a 50% duty cycle. This feature helps to eliminate flickering effects during modulation[1].

Another important factor when avoiding flickering in VLC is the frequency of operation. The human eye perceives fluctuations in light the switching speed is lower than around 200 Hz and lower frequencies are harmful to humans[2]. To avoid this effect, our transmitter works at 1 kHz.

Regarding replicability, the transmitter and receiver are controlled by Arduinos Nano, which are popular tools in schools, allowing a larger community to modify open-source platforms. The code, schematics, and 3D files will be made publicly available, containing all the required information.

At this stage, the prototype would already allow people to "see transmissions". This, however, would be a boring experience for children because they would see only two static boards with a normal light beam in between. Such a platform would be similar to existing kits using light for communication but developed for university students [15, 34]. A children's platform needs a more exciting application with engaging transmitters and receivers.

3.3 An engaging receiver with robots

Existing VLC platforms are *passive* and children learn more with *active* experiences [17]. To achieve this goal, we wanted a receiver that would *react* to the transmitted messages, so the children could have an interactive experience.

A key step to increase *user engagement* was the connection with teachers. The organizers of the event connected the research teams from country A to a teacher from a different country B. The teacher was part of a national educational campaign in her country of residence, where the government approved distributing a BBC micro:bit device. That device is a pocket-size computer designed by the BBC for use in schools [3]. Additionally, the teacher has used

[1]Flickering can cause headaches or seizures in people with epilepsy [13].
[2]Frequencies in the range 1-65 Hz induce seizures [13].
[3]Micro:bit: https://microbit.org/

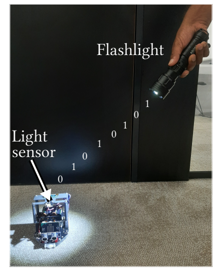


Figure 3: *T-light* second prototype. Using the robot as a receiver enables an interactive platform for children.

this educational computer connected to the micro:Maqueen Plus robot [4], which is a *"programming robot for STEAM education"*. In the teacher's country, the micro:bit platform is used by more than 12,000 students between seven and fourteen years old. Considering that the robot is a proven educational tool, we use the Maqueen Plus robot to develop our wireless link.

Figure 3 shows the second version of our prototype, where a flashlight sends wireless data to control the robot. The flashlight can send four commands: forward, backwards, right, and left. The transmitter's code keeps sending the instruction given by the last button pressed by the user until the user presses another button or the flashlight is turned off. The robot has a light sensor at the top, which is connected to an Arduinos Nano that decodes the message and forwards it to the robot to move it in the desired direction. To stop the robot, the transmission must be stopped by turning off the flashlight or pointing away the light from the robot. This last design approach is intended to make younger pupils understand the concept of range: the robot only receives the message when it is within range of the flashlight beam. The robot allows more interaction as the children "see" immediately the effect of sending different types of data and requires children to follow the robot in order to interact with it. *As we describe later, the ability to move with the platform proved instrumental in allowing children to discover, on their own, different phenomena in wireless communication.*

Another important factor is the effect of ambient light, which can diminish the performance of the system, as it affects the ability of the receiver to discern high and low levels, thus, the ability to successfully detect 1s and 0s. Because we have no control over ambient light and we intend to use the robots in different environments and moving within a room, we add an extra feature to the receiver, improving its versatility. The receiver samples the light sensor and adjusts the threshold dynamically based on the maximum and minimum values sampled over a sliding window. This adaptive adjustment allows the robot to differentiate between high and low light intensities, thus decode 1s and 0s, even under changing lighting conditions, as long as the sensor is not saturated.

3.4 An engaging transmitter: superheroes

For the last stage of the design, our team was expanded to two young adults, one woman and one man. The key advantage of involving younger people is their up-to-date connection with popular culture. One of the new team members suggested placing the

[4]Maqueen Plus V2: https://www.dfrobot.com/product-2026.html

flashlight (transmitter) inside an "Iron Man" armband, based on the popular Avenger Marvel movies, where Iron Man has a powerful laser radiating from his palm. Instead of a laser, we have our special flashlight. In this manner, wireless communication could be seen as a "superpower", where instead of shooting a laser beam or a spider web, the children shoot wireless commands that can be seen. This design creates further educational engagement, as research studies suggest a correlation between SciFi [2] and superheroes [5], and enhanced memory and learning.

Wearable "Iron (Wo)Man" armband (Transmitter). The final armband design, shown in Figure 4b, features a round-shaped flashlight, similar to the "Iron Man" palm depicted in Figure 4a, and four buttons that the student can use to control the robot.

Internally, the armband has an Arduinos Nano that reads the button pressed and controls the flashlight to send data. When we place the armband on a student, some children feel like a special suit is placed on them, making them feel like real superheroes. A pair of bands attached to the wearable are used to fix the light to the user's arm.

Tunable flashlight (Variable range). The flashlight has a tunable focus: its beam can change from long and narrow to short and broad. This design choice is not only to allow children to have one more feature to play with, a variable beam shape, but it has an educational purpose too: it can show the impact of range and coverage in wireless communication. If the robot gets further away from the child, the beam needs to be set long and narrow to reach a longer range.

The final prototype is shown in Figure 4c. For the manufacturing process of the armband and extra pieces for the robot, we used 3D printing with PLA, which is a lightweight material. The total weight of the armband and the robot are 200 g and 100 g, respectively.

4 Guided Activity

The final platform could be given as it is to children, so they could *see the wireless transmissions* while controlling the robot, but that unstructured approach would not convey clearly the key learning objective, which is to understand the basic principle of wireless communication. To communicate that learning objective, we designed a guided activity with two components: a short presentation and a game.

4.1 Presentation

Using our platform and a few slides, we present the concept of wireless communication to students in a three-minute demonstration. We start by showing that there are many lights in the fair but the robot does not respond to any of them. We also illuminate the robot with an unmodified flashlight, showing that it remains static. After that, we show how the robot moves when we use the special flashlight from the Iron (Wo)Man wearable, prompting students to consider what makes this light different.

We then use an animated slide to illustrate that as the light's frequency increases, the changes become invisible to the human eye, but a robot's sensors can still detect them. We explain that our special light changes intensity rapidly, enabling it to transmit various types of information, such as text, voice, images, and videos. Finally, we draw a parallel to how mobile phones and tablets use radio waves—an invisible type of light—to transmit information, emphasizing that these radio waves are constantly flowing around us, even though we cannot see them.

4.2 Game

After the presentation, we placed our armbands on the children and presented a game. The use of games for teaching, and more specifically for STEM, is a topic that has been explored in research before. In previous studies [4, 24], researchers show how a game can be an educator and a motivator for STEM careers. Based on guidelines proposed to build educational games [4], we designed a game using the final prototype and considering the feedback of five elementary and high school students, four girls and one boy. The final version of our game is described next.

Setup. The game setup includes a 1.2 m x 1.2 m area, a robot, an "Iron (Wo)Man" armband, six small 23 cm training cones, and three differently shaped and colored "target" tags. Within the delimited area, we place cones to act as obstacles. The three targets are placed as far away from each other as possible inside the area. Using this layout, shown in Figure 4d, the instructions for the game are as follows:

- First, the robot is placed in one corner of the area.
- Using the armband, the student should guide the robot to each target.
- Scoring: one point per target reached. There is a maximum time to reach all three targets.
- If the robot goes out of the delimited area, we manually return it to its last position.

5 Survey Study

Our work is motivated by an educational event organized by a supranational body. It had around 4,000 elementary and high school students, with teachers or parents, over two days. Held in a different country, it featured diverse cultural, socioeconomic, and linguistic backgrounds. The event had three official languages, including English, with translators provided for the other two. Snapshots of our participation are shown in Figure 5. We divided our booth into three zones. The demo area featured a screen for a short presentation on wireless communication with light and a demo of the "Iron (Wo)Man" armband and robot game. The other two zones were designated play areas for the game.

After the presentation, demonstration, and game, attendees were asked to fill out a voluntary and anonymous survey consisting of seven questions, as shown in Figure 6. The first three questions covered demographics: age, gender, and role (student, teacher, parent), with an option to skip these. The next three questions assessed understanding and interest: Did you find the topic interesting? Did you understand how light is used for communication? Would you like a lecture on this topic at your school? The final question invited general comments. About two-thirds of the attendees completed the survey, totaling 298 responses. We first present our findings based on demographics, followed by engagement and understanding levels.

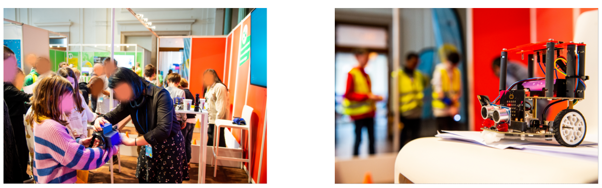
(a) Iron Man character with a powerful light beam in his palm (Credit: Marvel Studios).

(b) *T-light*'s armband based on the "Iron (Wo)Man" character.

(c) *T-light*'s third prototype: armband plus robot

(d) Design of the game for *T-light*'s: guide the robot to the targets avoiding the cones.

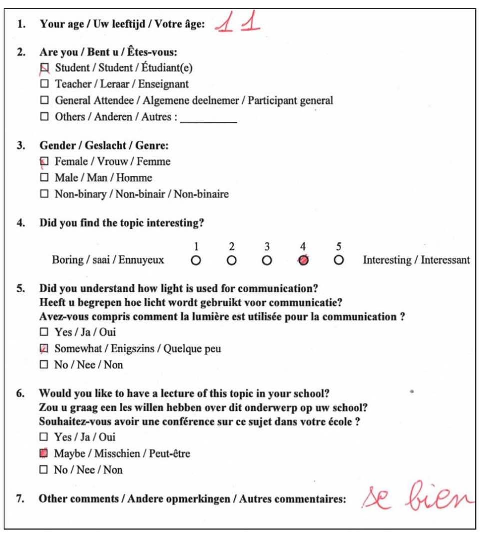
Figure 4: Design of the third prototype of *T-light*



(a) Large group of students.

(b) Small group of students.

Figure 5: Study at a large science fair. For example, the booth was visited by large groups (a), small groups (b).



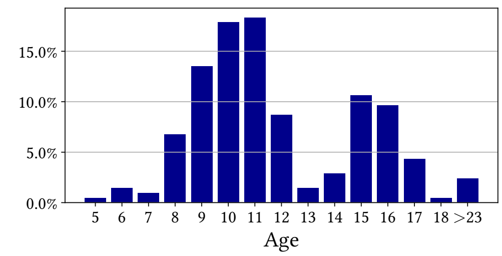
1. Your age / Uw leeftijd / Votre âge: 11
2. Are you / Bent u / Êtes-vous:
   - ☒ Student / Student / Étudiant(e)
   - ☐ Teacher / Leraar / Enseignant
   - ☐ General Attendee / Algemene deelnemer / Participant general
   - ☐ Others / Anderen / Autres : ________
3. Gender / Geslacht / Genre:
   - ☒ Female / Vrouw / Femme
   - ☐ Male / Man / Homme
   - ☐ Non-binary / Non-binair / Non-binaire
4. Did you find the topic interesting?
   Boring / saai / Ennuyeux 1 ○ 2 ○ 3 ○ 4 ● 5 ○ Interesting / Interessant
5. Did you understand how light is used for communication?
   Heeft u begrepen hoe licht wordt gebruikt voor communicatie?
   Avez-vous compris comment la lumière est utilisée pour la communication ?
   - ☐ Yes / Ja / Oui
   - ☒ Somewhat / Enigszins / Quelque peu
   - ☐ No / Nee / Non
6. Would you like to have a lecture of this topic in your school?
   Zou u graag een les willen hebben over dit onderwerp op uw school?
   Souhaitez-vous avoir une conférence sur ce sujet dans votre école ?
   - ☐ Yes / Ja / Oui
   - ☒ Maybe / Misschien / Peut-être
   - ☐ No / Nee / Non
7. Other comments / Andere opmerkingen / Autres commentaires: se bien

Figure 6: A sample of the voluntary anonymous survey.

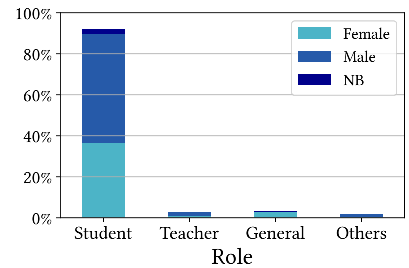
5.1 Demographics

Figure 7 shows the demographic information. Students represent 91 % of the attendees, teachers 3 %, general attendees 3 %, and others 2 %, less than 1 % of surveys provided no answer. Considering only the students' demographic, the first research question is: *What type of student was the most attracted to our booth?*

Finding 1: Age bias. About 70% of the surveys included age information, showing a bimodal distribution: peaks at ages 10-11 and 15-16. We can also observe a valley at age thirteen. We do not have statistics about all the fair's attendees or their engagement with the different booths. Thus, we do not know if 13-year-olds generally didn't engage with all the booths, or if they didn't find our platform appealing. As this age marks the start of puberty, further



(a) Age



(b) Role and gender

Figure 7: Demographic distribution of attendees based on voluntary survey. NB stands for Non-binary.

research is needed to identify engaging elements for this group. The positive outcome is that our design was made having children in mind and that group was the most present.

Finding 2: Gender bias. Our design team consisted of three women (a teacher, a young adult, and a researcher) and three men (a young adult and two researchers), but the booth attracted more males (55 %) than females (40 %). Non-binary accounted for 3 % and around 1 % of surveys provided no answer for gender. Without having the general attendance information for the fair, we do not know if this bias is only for our booth or the fair. However, later we discuss some further data from the survey that indicates that our platform needs to improve its engagement for females.

5.2 Engagement and understanding

Our presentation, demonstration, and game are not normal school lectures, and hence, no conclusive evidence can be drawn about learning goals. However, the survey provides some encouraging results regarding interest and understanding of the key learning objective: the basic principle of wireless communication. Some findings depend on the size of the group visiting our booth because it affected the type of interactions. Thus, first, let us describe the attendance pattern. The configuration of the event allowed the public to approach freely any booth, which led to three main types of group dynamics.

- *Large group (∼16 students).* After the presentation, we asked the person in charge, usually a teacher, to divide the group into four teams. Each team used one armband and one robot, two teams occupied one delimited area and the other two teams the other one. Each area had two robots placed at opposite corners of a square and the students competed against each other to reach their corresponding target.
- *Small group (<6 students).* The initial interaction was similar to the case of a large group, but we were able to elaborate on more concepts of wireless communications because students could explore the system for a longer period of time.
- *Individual.* This type of interaction involves a young student and one or both parents.

Based on the results of our survey and the size of the groups, we obtained the following findings.

Finding 3: A high level of interest and understanding. We noticed a high level of interest from the students, the young ones were particularly engaged and excited from the moment they were put on the "Iron (Wo)Man" armband. During the game, students needed to keep the light aimed at the robot and move closer if it moved too far. Children helped each other during the game, offering advice like "Make the light cover the robot's eye!" and "Stand closer to the robot!" These comments embed concepts of signal strength and range in wireless communications, which could be elaborated on in a longer lecture.

Most students grasped the following fundamental ideas about wireless communication:

- No light (no transmitter), the robot is still.
- Normal flashlight (no information), the robot is still.
- "Iron (Wo)Man" flashlight (transmitter with information), the robot moves according to the instructions.
- "Iron (Wo)Man" flashlight too far (weak signal), the robot is still.

These points, especially the first three, capture our main learning objectives, emphasizing that our special flashlight contains information that the robot understands, but only if the light is strong enough. Survey results confirmed our observations. On a scale from 1 to 5, 90% of attendees found the topic interesting (rating 4 or 5), 81% understood the basic idea of using light for wireless communication, and 68% wanted a further lecture on the topic. Feedback was overwhelmingly positive, with comments like "Fun," "Cool," "Nice," "Interesting," "Good," and thankful messages. These results validate that the *T-light* platform is engaging and effective in teaching the basics of wireless communication to children.

Finding 4: Small groups enable a deeper discovery and understanding. In education, a low student-to-teacher ratio is crucial for a good learning experience [12]. Our platform can help large classes understand basic communication concepts, but optimal results are achieved with a teacher monitoring groups of up to ten students. At the fair, large groups had limited time with the robot, focusing mainly on winning the game. They grasped basic communication concepts but couldn't explore details like *interference.* When two robots got too close, the overlapping (interfering) lights caused them to stop. Students noticed this, and we explained it as *interference*, but they quickly returned to the game.

On the other hand, smaller groups allowed for deeper exploration of unexpected outcomes. For example, we explained interference as two lights "talking" at once, making the robot unable to understand. Some students even started interfering intentionally with other robots as part of the game, similar to real-world communication *jamming*.

In an instance during quieter times, when there weren't many people around, children played freely with the platform and discovered new concepts. They learned they could control multiple robots with a broad light beam and "hack" each other's robots by blocking light with their bodies (*shadowing* effects). These unplanned outcomes demonstrate that allowing students extended free play during less crowded periods leads to deeper engagement and understanding of various wireless communication concepts.

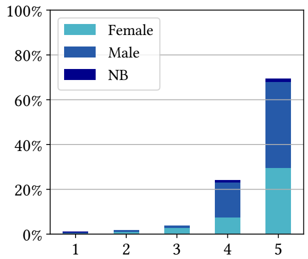
Finding 5: Heroines and heroes must come together. As stated before, our design team had three women and three men. We aimed to create a platform for all genders but recognized that a male hero might appeal more to males. The survey results reflect this. While understanding was similar (85% of females and 82% of males grasped the concept), engagement differed. Only 85% of females found the topic interesting, compared to 95% of males. Additionally, 56% of females wanted further lectures on the topic, versus 76% of males. This finding indicates that the main point of improvement for our platform is gender bias. One option we are considering as part of future work is using a heroine from Marvel, "Scarlet Witch", a powerful sorcerer that wears a red costume and sends intense fields of energy from her palms. Another option is to follow the route of Disney research, creating a magic wand that controls robots or other receivers that are more suitable to engage females.

Finding 6: High school students discover advanced concepts. Our platform, while designed for children, also engaged older students, particularly high schoolers, who had deeper questions about wireless communication. They asked about the effect of other light sources on the system, like an unmodified flashlight stopping the robot. This observation led to the discussion of the concept of *jamming*.

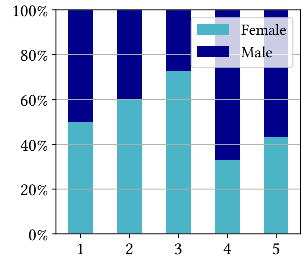
Regarding *interference*, which younger students also observed but were satisfied with our answer, the most advanced question we got from high school students was *"How is interference solved for mobile phones?"* This question reflects a high level of abstraction because, based on our discussion, the student was able to build a similarity between *T-light* and the cellular network, with the armbands playing the role of *cellular stations* transmitting data and the robots playing the role of *cell phones* receiving that data. This question highlights the ability of our platform to motivate curiosity-driven questions about real wireless systems.

6 Discussion

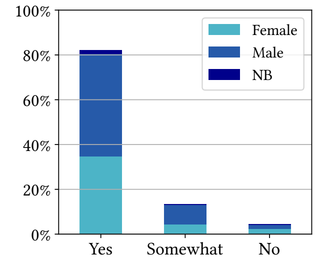
The diversity in student ages, group sizes, and interaction time brought significant challenges for our system in achieving its goal of teaching wireless communication, particularly using light. Although the objective was partially met, the system needs improvements to address issues detected during the educational event, which will serve as insights for future testing in visiting schools.



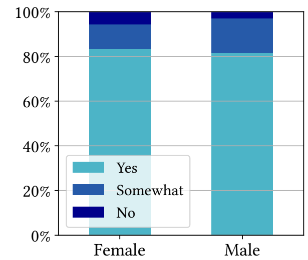
(a) ***"Did you find the topic interesting?"*** **From Boring(1) to Interesting(5)**



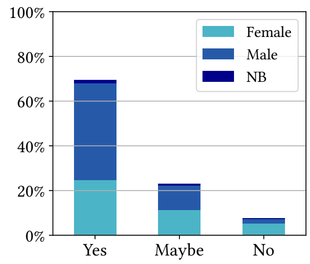
(b) Normalized interest by gender. Males find the topic more interesting.



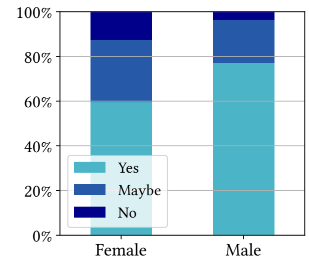
(c) ***"Did you understand how light is used for communication?"***



(d) Normalized understanding by gender. Females perform slightly better.



(e) ***"Would you like to have a lecture of this topic in your school?"***



(f) Normalized interest in a lecture by gender. Males are more interested.

Figure 8: Second set of questions of the voluntary survey.

Age difference. The wide age range of the participants required adapting engagement strategies based on their age group. The introduction of a popular Marvel character as inspiration for the system's functionality helped to unify the effort to engage a diverse audience. However, the brief presentation did not fully take into account the different learning processes of different age groups. The pace, pitch and demos were sufficient to engage younger pupils, while older pupils could have benefited from a faster and more direct approach, and leveraging the rest of the time to introduce concepts such as other encoding formats, modulation, and multiplexing.

Language barrier. Language played a paramount role in the way participants grasped the concepts conveyed by the *T-light* platform, especially during the presentation and the explanation of how to *play* with the robot. Younger pupils often spoke only their mother tongue (Spanish, French, and Dutch), while older students had a good command of English. Although volunteer translators helped bridge the language gap, the translation slowed down the pace of the process and some technical terms were not entirely or accurately conveyed.

Group size. The dynamics of the interaction with *T-light* was influenced by the group size. In large groups, it was difficult to maintain attention. We addressed this challenge by relying on the tutor or guardian during the presentation and by dividing the group into smaller groups, which required all of our team members to work simultaneously. Each team member in charge of a group handled the questions from those pupils. For small groups or individuals, the process was more interactive with the platform and with our team members. Regardless of the group size, according to the survey results, the teaching goals were satisfactorily met for both small and large groups.

Event format. The organization of the educational event allotted 10 minutes for a group to visit each booth. In general, this was manageable for our team, and in most cases, the time constraints were met to present the basic concepts and allow interaction with the robot. However, during the peak hours of event attendance, the amount of pupils was difficult to handle, causing some of them to focus solely on playing with the robot. The game design compensated for these drawbacks since it was designed to provoke situations in which concepts such as wireless data transmission, range, overlap, and light intensity arose as questions from the students.

7 Future Work

In this section, we reflect on our methods and findings and describe limitations that can be tackled in future work.

7.1 Enhancing interaction

Our *T-light* system limits the use of the "Maqueen" robot to movement. However, the robot features different input and output devices that could increase its appeal to children, which is the original design intention of the robot. For example, it is equipped with a speaker and buzzer, which can be used to signal the reception of instructions, report when the robot reaches a goal, or alert when *jamming* or *interference* appear by making special sounds for each case. Additionally, this educational robot features an LED matrix that can display messages or symbols, such as arrows, that indicate the current instruction the robot is executing. These sensory feedback methods are relevant in human-robot interaction as they allow two-way communication in which the participant receives confirmation from the robot that it understands the instruction, *rewarding* the use with the task execution. In this manner, more senses could be involved in the learning process.

7.2 A more inclusive setup

A report from UNESCO states that *"long-standing biases and gender stereotypes are steering girls and women away from science-related fields"* [7], while other studies show an under-representation of women and minorities in STEM. *T-light*'s aim is to be an inclusive platform. We obtained an initial participation of 40 % of women, which is encouraging but there is still work to do.

We chose "Iron Man" because it had a light on his palms, but to create a more inclusive experience, we plan to diversify our character selection, including options like Wonder Woman or Scarlet Witch, who use bracelets or energy beams. These characters require different colors for the transmitter and, as our design is 3D printed using PLA, there are plenty of options to match other superheroes' and superheroines' attire, or to reflect color preferences of the users. Furthermore, our studies revealed that our design is not very comfortable for left-handed users. A potential solution is to re-design our transmitter to match left-handed users or design a new ambidextrous version for both left- and right-handed users. These changes will help make our system more gender and user-inclusive.

7.3 Learning potential of *T-light*

The current setup of *T-light* is simple and lightweight, which allows children to perform their own discoveries. Our experiences at the fair have motivated us to enhance our design to demonstrate other wireless principles. The most important one would be to showcase interference and multiplexing.

Both types of users, children and teenagers, uncovered the issue of *interference*. We were happily surprised to see that it was easily discovered because it is one of the most fundamental issues in wireless communication. To teach a solution for this issue, we could use RGB lights (red-green-blue). These lights could initially transmit a message using all three colors, generating *white light*, as with the current platform, and causing interference when two lights collide. Then, we could have a button to change the color of the lights (different channels). This color change could show that even when two lights shine over two robots, each robot could avoid interference by following the instructions of their corresponding "channel".

A game design that introduces the concept of multiplexing could involve the participation of teams, each team using a color channel to achieve a common collective goal using channel-specific transmitters and channel-specific robots. In this way, users realize they can only remotely control robots from their team, based on the light color.

7.4 Ethical participation of children

The *T-light* platform was designed for a supranational science fair organized by an international body. Following an open call, our proposal was approved. The organizers informed schools about the event, and a public description of all booths was provided. The teachers of each participating school handled the authorization from the parents or legal guardians. To collect the data from the children, we first consulted the organizers, explaining that the information was going to be collected using an anonymous and voluntary survey. After the children *"played"* with our platform, we asked permission from the guardian (parent or teacher) to complete the survey and explained the use of the data. We emphasized that the survey is *anonymous*, as no personal or identifiable information is collected; and *voluntary*, approximately one-third of the attendees opted for not filling up the survey, and from the two-thirds that filled up the survey, some decided to leave some questions blank.

In addition to the process followed by the supranational institution, we also contacted the Ethics Review Board of our university. We explained our protocol for data collection and storage. Our request was approved by our institution's board. The figures showing the people at the event are the official pictures, taken by the organizers, and they satisfy all the necessary consent forms and privacy of children, which does not allow the publishing of frontal pictures of minors.

8 Conclusion

In this study, we proposed a sensory approach to teach wireless communications to a wide range of students, from elementary to high school. The design is built upon various proven educational concepts, such as using interactive robots, superheroes and games. Our studies, with hundreds of students, show a high level of interest and understanding. These studies also provided valuable findings to improve the platform further and make it more inclusive. Our vision is to provide future citizens with a basic understanding of a technology that is pervasive but difficult to grasp.

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