Frontiers of Information Technology & Electronic Engineering

Wearable devices and IoT applications for detecting symptoms, infected tracking and diffusion containment of the Covid-19 Pandemic: a survey

--Manuscript Draft--

Manuscript Number:	ZUSC-D-21-00085R1
Full Title:	Wearable devices and IoT applications for detecting symptoms, infected tracking and diffusion containment of the Covid-19 Pandemic: a survey
Article Type:	Review
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Abstract:	Until a safe and effective vaccine to fight the SARS-CoV-2 virus will be developed and available for the global population, preventive measures, such as wearable tracking and monitoring systems supported by internet of things (IoT) infrastructures are valuable tools to contain the pandemic. This review paper analyses innovative wearable systems for limiting the virus spread, early detecting the first symptoms of the COVID (coronavirus disease)-19 infection, and remotely monitor the health conditions of infected patients during the quarantine. The attention is focused on systems allowing quick user screening through ready-to-use hardware and software components. Such sensor-based systems monitor the principal vital signs, early detecting symptoms related to COVID-19 and alert patients and medical staff. Novel wearable devices for complying with the social distance rules and limiting the interpersonal contagion (such as smart masks) are investigated and analysed. Besides, an overview of implantable devices for monitoring the effects of COVID-19 on the cardiovascular system is presented. Afterwards, we report an overview of tracing strategies and technologies for containing the COVID-19 pandemic based on IoT technologies, wearable devices, and cloud computing. In detail, we demonstrate the potential of RF (radio frequency)-based signals technology, including Bluetooth low energy (BLE), WiFi and RFID (radio frequency identification), often combined with apps and cloud technology. Finally, the critical analysis and comparisons of the different discussed solutions are presented, highlighting their potentialities and providing new insights for developing innovative tools for facing future pandemics.
Response to Reviewers:	Dear Editorial Board of Frontiers of Information Technology & Electronic Engineering Dear Editors-in-Chief

	Dear Reviewers We have carefully assessed the reviewers' comments, and thus, we have integrated and improved the revised version of the manuscript; in the submitted file "ANSWER TO REVIEWERS COMMENTS", we reported each reviewer comment and our related improvements added in the revised manuscript (highlighted with red colour). We are confident that the integrations made can fully meet the reviewers' requests. We look forward to receiving your feedback. Sincerely The authors

June 1st 2021,

Dear Editorial Board of *Frontiers of Information Technology & Electronic Engineering*
Dear Editors-in-Chief

On behalf of all authors, I resubmit our revised paper, entitled "*Wearable devices and IoT applications for detecting symptoms, infected tracking and diffusion containment of the Covid-19 Pandemic: a survey*", to *Frontiers of Information Technology & Electronic Engineering* journal. The authors declare that they have no real or potential conflict of interest in conjunction with submission of this manuscript.

We have carefully assessed the reviewers' comments, and thus, we have integrated and improved the revised version of the manuscript; in the following, we report each reviewer's comment and our related improvements added in the revised paper (highlighted with red colour).

Relatively to the first comment of Reviewer 1:

1- *"The authors should eliminate the current grammatical and punctuation mark errors and also confirm the correct scientific English."*

We gratefully thank the reviewer for the comment; we carefully reviewed the whole article to improve the English language and correct the typos and grammatical and punctuation mark errors.

Relatively to the second comment of Reviewer 1:

2- *"The authors should write the complete terms of all abbreviations (including the instruments) before the first use in the abstract and main manuscript."*

We gratefully thank the reviewer for the comment; we checked the whole manuscript and clarified all the acronyms at the first appearance.

Relatively to the third comment of Reviewer 1:

3- *"The authors should clearly explain the innovation and importance of their work on the introduction of the manuscript. They should justify the value of the work and compare their work with previously similar published papers."*

We gratefully thank the reviewer for the comment; we added to the introduction (on page 4) some sentences to highlight the novelty and contributions of the proposed scientific work.

- *"To our knowledge, a review work so comprehensive and in-depth wasn't present in the scientific literature, concerning not only prototypes derived by scientific works but also commercial and post-development devices next to the commercialization phase. In particular, the presented study considers a wide range of last-generation wearable and portable devices reported both in the scientific literature and present on the market to detect the symptoms featuring the COVID-19 disease, remotely monitor infected patients, trace the contagion chain, and follow the patient's post-illness status. Furthermore, novel IoT tracing systems, also supported by wearable devices, are deeply explored, focusing on the* *numerous solutions proposed by research centres and governmental bodies during the two years 2020/2021 to contain the COVID-19 pandemic. The aim is to cover as many technologies and solutions as possible to provide the reader with a comprehensive view of the treated topics. Finally, a critical analysis of the different devices and strategies is reported, providing a comparison to bring out potential and shortcomings helpful in developing the tools to tackle future pandemics; we consider this one of the main contributions offered by the proposed work."*

Furthermore, we added some sentences in the conclusions section (on page 41) to compare the proposed review work with similar published papers.

- *"Our scientific work focuses on applications based on wearable devices for fighting against the COVID-19 pandemic, including the extremely popular traceing mobile applications, unlike similar review papers that range over other monitoring solutions (drones, robotic applications, etc.) (Nasajpour et al. 2020; Al-Humairi and Kamal 2021). Furthermore, review papers covering the same topics do not always consider commercial devices, including intelligent masks, extensively investigated in the proposed research work (Chamola et al., 2020; Suresh Kumar et al., 2021). Besides, in our review paper, we dedicated a entire section to wearable commercial solutions (e.g. smart badge, smartwatches, smart bracelets, etc.) for complying with the social distancing rules, mainly in workplaces, which are allowing a rapid and safe resumption of economic activities; similar works rarely consider this topic (Yousif et al., 2021). Finally, we also explored several wearable and implantable applications for monitoring the effects of COVID-19 disease on the cardiovascular system, usually not covered by similar works (Hedayatipour and Mcfarlane 2020; Behar et al., 2020). Therefore, we believe that the accuracy and completeness of the proposed scientific work represent its actual added value, providing the reader with a comprehensive overview of the IoT-based solutions to tackle the COVID-19 pandemic."*

Also, the following bibliographic references were added for comparison purpose:

- Nasajpour, M., Pouriyeh, S., Parizi, R.M., Dorodchi M., Valero, M., Arabnia, H.R. 2020 Internet of Things for Current COVID-19 and Future Pandemics: an Exploratory Study. *J Healthc Inform Res* **4**:325–364. https://doi.org/10.1007/s41666-020-00080-6

- Al-Humairi, S.N.S., Kamal, A.A.A. 2021. Opportunities and challenges for the building monitoring systems in the age-pandemic of COVID-19: Review and prospects. *Innov Infrastruct Solut* **6**:1–10. https://doi.org/10.1007/s41062-020-00454-0.

- Chamola V., Hassija V., Gupta V., Guizani M. 2020 A Comprehensive Review of the COVID-19 Pandemic and the Role of IoT, Drones, AI, Blockchain, and 5G in Managing its Impact. *IEEE Access* **8**:1-12. https://doi.org/10.1109/ACCESS.2020.2992341

- Yousif, M., Hewage, C., Nawaf, L. 2021. IoT Technologies during and Beyond COVID-19: A Comprehensive Review. *Future Internet*, **13**:1–24. https://doi.org/10.3390/fi13050105.

- Hedayatipour, A., Mcfarlane, N. 2020 Wearables for the Next Pandemic. IEEE Access **8**:184457–184474. https://doi.org/10.1109/ACCESS.2020.3029130

- Behar J. A., Liu C., Kotzen K., Tsutsui K., Corino V.D.A., Singh J., Pimentel M.A.F., Warrick P., Zaunseder S., Andreotti F., Sebag D., Kopanitsa G., McSharry P.E., Karlen W., Karmakar C., Clifford G.D. 2020. Remote health diagnosis and monitoring in the time of COVID-19. Physiol Meas **41**:1–30. https://doi.org/10.1088/1361-6579/abba0a

Relatively to the fourth comment of Reviewer 1:

4- *"The authors should cite important references. The below reference is suggested to be cited in the revised manuscript: International journal of molecular sciences 21 (14), 5126 (2020)."*

We gratefully thank the reviewer for the comment; we added some important references and related discussion in section 2.1 ("*Overview of innovative masks for limiting the COVID-19 spreading*") on pages 15 and 16:

- *" In (Rabiee et al., 2020), the authors developed a point-of-use rapid detection of the COVID-19 virus in the form of a mask coated by metallic NPs doped with an organo-metallic framework; the interaction with the virus changes the optical properties of NPs, resulting in a colour variation of the mask's surface. Besides, the authors propose an overview of the different diagnosing methods and techniques for rapid detection of COVID-19 using optical techniques, exploiting the easy absorption/desorption of the nanostructured materials (i.e. Gold, Silver, Magnetic and metal-organic NPs) (Ghasemi et al., 2015; Rabiee et al., 2020; Nejad et al., 2020). The aim is to develop point-of-care solutions to take over the presence of a virus or even its concentration in the air in a rapid and non-invasive way (de Fazio et al., 2021). Also, in (Giovannini et al. 2021), the authors investigated the different techniques and critical technical aspects for detecting virus by analysing the exhaled breath, including electrochemical, chemoresistive, biological gas sensors or the breath's liquid phase (i.e. EBA-exhaled breath aerosol or EBC- exhaled breath condensate) using PCR-based (polymerase chain reaction) detection methods."*

Particularly, the bibliographic references added to the manuscript are the following:

- Ghasemi, F., Hormozi-Nezhad M.R., Mahmoudi M. 2015. A colorimetric sensor array for detection and discrimination of biothiols based on aggregation of gold nanoparticles. *Analytica Chimica Acta* **882**:58–67. https://doi.org/10.1016/j.aca.2015.04.011

- Rabiee N, Bagherzadeh M, Ghasemi A, Zare A, Ahmadi S, Fatahi Y, Dinarvand R, Rabiee R, Ramakrishna S, Shokouhimehr M, Varma R (2020) Point-of-Use Rapid Detection of SARS-CoV-2: Nanotechnology-Enabled Solutions for the COVID-19 Pandemic. Int J Mol Sci 21:1–24. https://doi.org/10.3390/ijms21145126

- Nejad, M.A.F., Bigdeli A., Hormozi-Nezhad M.R. 2020 Wide color-varying visualization of sulfide with a dual emissive ratiometric fluorescence assay using carbon dots and gold nanoclusters. *Microchemical Journal* **157**:1-8. https://doi.org/10.1016/j.microc.2020.104960

- de Fazio R., Sponziello A., Cafagna D., Velazquez R., Visconti P. 2021 An overview of technologies and devices against COVID-19 pandemic diffusion: virus detection and monitoring solutions. International Journal on Smart Sensing and Intelligent Systems **14**:1-28. https://doi.org/10.21307/ijssis-2021-003

- Giovannini, G., Haick, H., Garoli. D. 2021. Detecting COVID-19 from Breath: A Game Changer for a Big Challenge. ACS Sens **6**:1408–1417. https://doi.org/10.1021/acssensors.1c00312

Relatively to the fifth comment of Reviewer 1:

5- *"The all figure captions should be revised to cite the related references under each figure. The reuse permission of the figures should be provided. All the images should have proper citation recognition and references."*

We gratefully thank the reviewer for the comment; we checked all the figure captions placing the corresponding bibliographic reference.

Relatively to the sixth comment of Reviewer 1:

6- *"The quality of the figures should be improved."*

We gratefully thank the reviewer for the comment; we carefully checked all the figures present in the manuscript substituting most of them with high-quality versions and improving the quality of the others.

We thank Reviewer 2 for the positive evaluation of our scientific work related to its quality and organization.

Relatively to the comment of Reviewer 2:

1- *"I have only a minor comment, concerning the critical analysis of social distancing and contact tracing solutions. The authors do not take in any consideration possible privacy issues related to such applications. To which extent do the presented applications deal with privacy notions? Which measures do they adopt to preserve the privacy of users? Some considerations about these aspects might be added in Section 5. There are also research works which go in such direction, for example:*

- Kuhn et al. "Covid Notions: Towards Formal Definitions - and Documented Understanding - of Privacy Goals and Claimed Protection in Proximity-Tracing Services" https://www.sciencedirect.com/science/article/pii/S2468696421000094

- Sun et al. "An Empirical Assessment of Global COVID-19 Contact Tracing Applications" https://arxiv.org/pdf/2006.10933.pdf"

We gratefully thank the reviewer for the comment; we added some sentences from page 40 to 41 with the considerations related to the solutions and protocols for preserving privacy and anonymity in contact tracing applications.

- *"The fundamental aspect related to the collection of social interaction data is the privacy implication. Different strategies are available for managing the data collection: centralized, semi-centralized, and decentralized. In the first one, the user periodically sends the Bluetooth device IDs to a backend service; in the semi-decentralized approach, the relation between the app and the device ID is remotely stored, whereas the contact information is collected on the local device (BlueTrace 2020). In contrast,* *in a decentralized solution, the Bluetooth device IDs related to the social contacts are stored in the local devices, sending them only when the user tests positive. The contact data should be collected into a remote central database in an encrypted manner for protecting it from dumping and data branches. For instance, the GoCoronaGo system uses a centralized approach based on Unique ID and Device ID assigned by the central server during the installation phase to keep user anonymity (Simmhan et al., 2020). TraceTogether app employs IDs assigned by the central server or locally generated during the contact tracing activity (TraceTogether Tokens, 2020). Thus, the system doesn't need any personal data related to the user, recognized only by a random ID periodically changed. In contrast, the Immuni app paradigm recently switched from a centralized to a decentralized approach to enhance privacy protection. Particularly, the user smartphone locally collects the random IDs of close people, produced according to a key stored in the device during the installation process. If the user contracts the virus, an unlock code is provided to transfer the acquired IDs to the central server (Immuni,2020). The semi-centralized approach is used by BlueTrace and Aarogya Setu (Aarogya Setu, 2020) applications developed by the Australian and Indian governments to face the COVID-19 pandemic.*

Usually, the tracing apps are supported by geolocalization data provided by a GPS receiver, stored inside a local SQLite database on the smartphone, making them periodically available to the central server.

In (Kuhn et al., 2021), the authors explored the numerous protocols proposed by the scientific community for guaranteeing the privacy and anonymity of collected tracking information according to the data protection rules; the analysed protocols concern both the centralized and decentralized approaches (such as decentralized privacy-preserving proximity tracing DP3T (DP-3T, 2021), Google-Apple exposure notification framework GAEN (Apple Inc., 2021), pan-European privacy-preserving proximity tracing PEPPT-PT (PEPP-PT, 2020), ROBERT- ROBust and Privacy-PresERving Proximity Tracing protocols (PRIVATICS team Inria and Fraunhofer AISEC 2021), etc.). Furthermore, the authors proposed a critical analysis of the considered approaches to highlight their strengths and weaknesses. Finally, the reported discussion indicated none of the discussed protocols could ensure localization and identity protection from users and server points of view. In particular, a centralized approach could expose the localization data of alerted users, as well as for the hybrid solutions, such as DESIRE (2020b) and ConTraCorona protocols (Beskorovajnov et al., 2020).

In this context, R. Sun et al. developed a security and privacy detection method, called COVID GUARDIAN, which identifies the shortcomings of the protection systems by combining three steps: PII (personal identification information) analysis, dataflow analysis to detect privacy hazards, and malware detection (Sun et al., 2020). Using this developed assessment method, the authors tested 40 apps, including TraceToghether, COVIDSafe (Health ,2020), Aarogya Setu, etc.; the obtained results demonstrated that no application could completely safeguard users' security and privacy from all threads."

Furthermore, the bibliographic references added to the review article are:

- BlueTrace (2020) BlueTrace, a privacy-preserving protocol for community-driven contact tracing across borders. https://bluetrace.io. Accessed 31 May 2021

- Aarogya Setu (2020) Aarogya Setu Mobile App. In: MyGov.in. https://mygov.in/aarogya-setu-app/. Accessed 31 May 2021

- Kuhn, C., Beck. M., Strufe, T. 2021 Covid notions: Towards formal definitions – and documented understanding – of privacy goals and claimed protection in proximity-tracing services. *Online Social Networks and Media* **22**:1-17. https://doi.org/10.1016/j.osnem.2021.100125

- Apple Inc. (2021) Privacy-Preserving Contact Tracing - Apple and Google. In: Apple. https://www.apple.com/covid19/contacttracing. Accessed 31 May 2021

- DP-3T (2021) Decentralized Privacy-Preserving Proximity Tracing -- Documents. https://github.com/DP-3T/documents. Accessed 31 May 2021

- PEPP-PT (2020) Pan-European Privacy-Preserving Proximity Tracing. PEPP-PT Documentation. In: GitHub. https://github.com/pepp-pt. Accessed 31 May 2021

- PRIVATICS team Inria and Fraunhofer AISEC (2021) ROBust and Privacy-PresERving Proximity Tracing Protocol, Technical report. https://github.com/ROBERT-proximity-tracing/documents. Accessed 31 May 2021

- Castelluccia C., Bielova N., Boutet A., Cunche M., Lauradoux C., Métayer D.L., Roca V. 2020 DESIRE: A Third Way for a European Exposure Notification System Leveraging the best of centralized and decentralized systems. *arXiv:200801621 [cs]*: 1–17

- Beskorovajnov W., Dörre F., Hartung G., Koch A., Müller-Quade J., Strufe T. 2020 ConTra Corona: Contact Tracing against the Coronavirus by Bridging the Centralized–Decentralized Divide for Stronger Privacy. *IACR Cryptol. ePrint Arch*:**2020**:1-47.

- Sun, R., Wang, W., Xue, M., Tyson, G., Camtepe, S., Ranasinghe, D.C. 2020. An Empirical Assessment of Global COVID-19 Contact Tracing Applications. *arXiv e-prints*, **2006**:1–13

- Health AGD (2020) COVIDSafe app. In: Australian Government Department of Health. https://www.health.gov.au/resources/apps-and-tools/covidsafe-app. Accessed 31 May 2021

Best regards

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Wearable devices and IoT applications for detecting symptoms, infected tracking and diffusion containment of the Covid-19 Pandemic: a survey

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Received: xx.xx.xxxx Accepted:xx.xx.xxxx

Abstract - Until a safe and effective vaccine to fight the SARS-CoV-2 virus will be developed and available for the global population, preventive measures, such as wearable tracking and monitoring systems supported by internet of things (IoT) infrastructures are valuable tools to contain the pandemic. This review paper analyses innovative wearable systems for limiting the virus spread, early detecting the first symptoms of the COVID (coronavirus disease)-19 infection, and remotely monitor the health conditions of infected patients during the quarantine. The attention is focused on systems allowing quick user screening through ready-to-use hardware and software components. Such sensor-based systems monitor the principal vital signs, early detecting symptoms related to COVID-19 and alert patients and medical staff. Novel wearable devices for complying with the social distance rules and limiting the interpersonal contagion (such as smart masks) are investigated and analysed. Besides, an overview of implantable devices for monitoring the effects of COVID-19 on the cardiovascular system is presented. Afterwards, we report an overview of tracing strategies

and technologies for containing the COVID-19 pandemic based on IoT technologies, wearable devices, and cloud computing. In detail, we demonstrate the potential of RF (radio frequency)-based signals technology, including Bluetooth low energy (BLE), WiFi and RFID (radio frequency identification), often combined with apps and cloud technology. Finally, the critical analysis and comparisons of the different discussed solutions are presented, highlighting their potentialities and providing new insights for developing innovative tools for facing future pandemics.

1. Introduction

Globally, as of 11 February 2021, there have been more than 106.990.000 confirmed cases of COVID (coronavirus disease)-19, including over 2.347.000 deaths, reported by the world health organization (WHO). The virus has been contracted in almost every continent, as shown in the following Figure 1a and 1b. Furthermore, the Pandemic is causing severe damage to the economic systems of each country. Figure 2 shows the gross domestic product (GDP) growth rate of the EU (European Union) countries and the related forecasts for 2021. In 2020, all the nations belonging to the Euro area suffered from reduced GDP between 4% and 10% (Figure 2a). However, forecasts for 2021 indicate a strong rebound in GDP with a mean increase higher than 4% (Figure 2b).

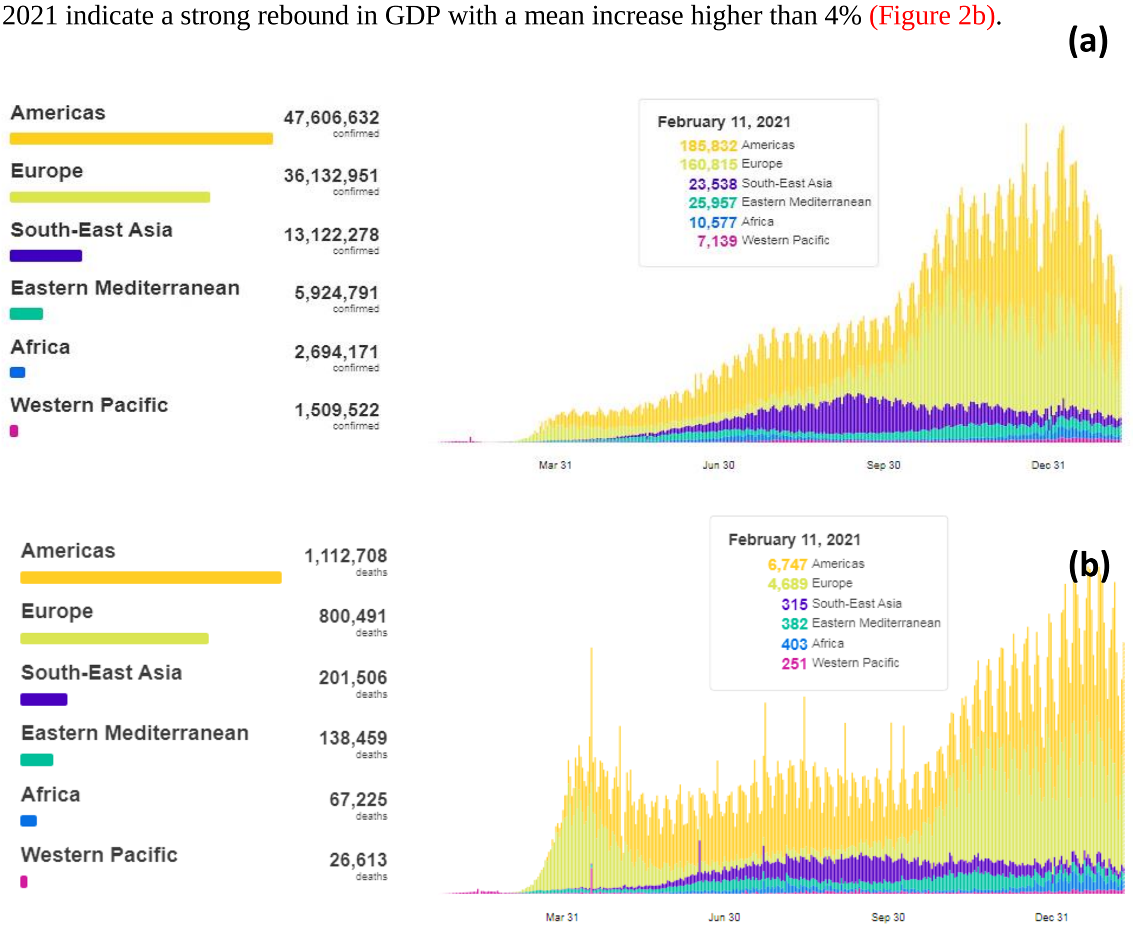


Figure 1. Trends of infections (a) and deaths (b) with the COVID-19 by continent (World Health Organization, 2020).

The virus continues to affect every region of the world, and while some countries appear to have primarily controlled the virus, others are experiencing high and rising infection rates. To reduce transmission and control the epidemic as soon as possible, the scientific community focuses on different critical activities. In this context, technology constitutes a powerful tool to monitor the user parameters remotely, determine health issues, and make decisions about the most suitable therapy improving the user's lifestyle (Visconti *et al.*, 2018; Gaetani *et al.*, 2019; Visconti *et al.*, 2019). In particular, the scientific community is developing contact tracking processes. Contact tracing is the process of identifying, assessing, and managing people who have been exposed to a disease to prevent onward transmission. Contact tracing for COVID-19 requires identifying persons who may have been exposed to COVID-19 and following them up daily for 14 days from the last point of exposure. The process is challenging to put into practice as it takes a long time and, above all, because the virus can be transmitted between people without evident symptoms.

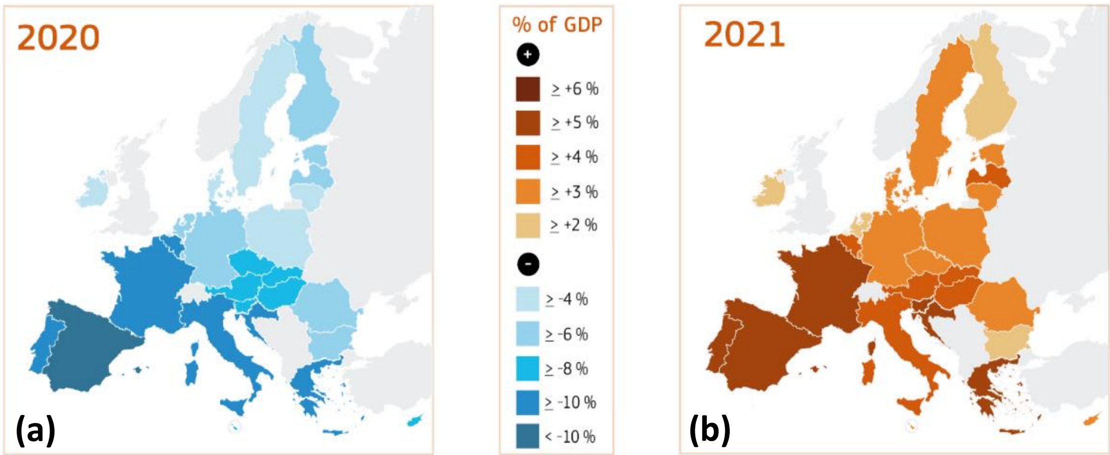


Figure 2. Geographic maps of the Gross Domestic Product (GDP) growth rate of the EU countries in 2020 (a), and as expected for 2021 (b) (European Commission, 2020).

Therefore, remote diagnostic and monitoring methods of patients' health status become fundamental for reducing the virus's spread (Donaghy *et al.*, 2019; CDC, 2020; 2020). The diagnostic and monitoring methods involve considerable data processing difficulties, particularly regarding data security and privacy (Rights (OCR) 2020). The wearable devices have an enormous potential to curb the spread of the COVID-19 pandemic, as well as other infective diseases. Several efforts have been made in the last months by the scientific community and companies to develop advanced, portable, low-power, and multifunctional wearable devices to detect the onset of the symptoms of COVID-19 disease (such as fever, cough, reduced blood oxygenation (i.e. low SpO_2), increased heart-rate variability-HRV, etc), and thus intervene more quickly before the deterioration of the patient's physical condition.

This manuscript investigates the different internet of things (IoT) solutions and wearable sensing devices reported on the market and in the scientific literature used to early detect symptoms featuring the COVID-19 disease. Specifically, wearable devices and the IoT system are currently employed by hundreds of millions of people worldwide to detect different biophysical and environmental parameters, such as body temperature, heart rate, SpO_2, and respiration rate. These devices, supported by cloud platforms and mobile applications, can continuously and real-time process the acquired information for detecting the early stages of the infection. Afterwards, an overview of the different wearable solutions for complying with the social distancing rules; particularly, the main countermeasures to reduce the spreading of COVID-19 pandemic are the use of the mask and social distancing. Thus, several solutions have been developed for aiding workers to keep and check the social distancing in the workplaces allowing the continuation of production activities. Different models of smart masks have been considered and analysed, as an essential tool for continuing the pandemic diffusion, as suggested by the WHO guidelines.

Furthermore, recent studies demonstrate a correlation between cardiovascular diseases and COVID-19; therefore, we have investigated the implantable solution for remotely monitoring heart conditions. Also, state of the art concerning the tracing systems for containing the COVID-19 pandemic is reported. In fact, companies and state governments, already from the first months of the pandemic's start, have introduced tracing applications for tracking the citizen's movements and, thus, rebuild the contagion chain once a user is found to be infected, limiting the pandemic's spreading. Finally, we have carried out critical analysis and performance comparisons about the discussed applications, pointing out the advantages, limitations, and future potentialities to obtain the tools to face future pandemics.

To our knowledge, a review work so comprehensive and in-depth wasn't present in the scientific literature, concerning not only prototypes derived by scientific works but also commercial and post-development devices next to the commercialization phase. In particular, the presented study considers a wide range of last-generation wearable and portable devices reported both in the scientific literature and present on the market to detect the symptoms featuring the COVID-19 disease, remotely monitor infected patients, trace the contagion chain, and follow the patient's post-illness status. Furthermore, novel IoT tracing systems, also supported by wearable devices, are deeply explored, focusing on the numerous solutions proposed by research centres and governmental bodies during the two years 2020/2021 to contain the COVID-19 pandemic. The aim is to cover as many technologies and solutions as possible to provide the reader with a comprehensive view of the treated topics. Finally, a critical analysis of the different devices and strategies is reported, providing a comparison to bring out potential and shortcomings helpful in developing the tools to tackle future pandemics; we consider this one of the main contributions offered by the proposed work.

This review paper is arranged as follows: in section 2, an overview of different IoT solutions and wearable sensing devices is reported to detect the firsts symptoms of COVID-19 disease. In addition, in subsection 2.1, various models of smart masks for safety and detection purposes are analyzed, as well as subsection 2.2, an analysis on implantable devices for detecting the effects of

COVID-19 disease on the human body are presented. Section 3 introduces an overview of wearable solutions to help users maintain social distancing in the workplace and not only, whereas, in section 4, the state of art about the tracing systems for containing the COVID-19 is reported. Finally, in section 5, we carry out performance comparisons and critical analysis about the devices, technologies and architectures described in the previous sections.

2. IoT Solutions and Wearable Sensing Devices to tackle against the COVID-19 Pandemic

In this paragraph, we have explored innovative wearable solutions reported in scientific works aimed to detect the onset of the first symptoms related to the COVID-19 disease, such as fever, cough, respiratory issues, low blood oxygenation, but also innovative sensors for detecting the infected people in a rapid and non-invasive manner. Different solutions are proposed in the scientific literature for remote tracking and monitoring patients' vital signs for early detecting the worsening of their conditions (Chung *et al.*, 2020; Greenhalgh *et al.*, 2020; Menni *et al.*, 2020).

The body temperature is the primary indicator of an eventual contagion by the COVID-19 virus; for body temperature higher than 37.5 °C, it is suggested to the patient get into self-quarantine to avoid an eventual diffusion of the pandemic and carry out RT-PCR (reverse transcriptase-polymerase chain reaction) test. Therefore, solutions for remotely monitoring the body temperature have been presented on the market or proposed in scientific works. M. Modal *et al.* have proposed a low-cost and lightweight solution for remotely monitor the body temperature, ensuring a 98% accuracy (Mondal *et al.*, 2020). The resulting wearable design is comfortable and can be integrated into our daily lives amid the current COVID-19 pandemic. Besides, in (Chen *et al.*, 2020), the authors developed an in-ear thermometer for monitoring the body temperature with the smartphone's support. Also, several watch-type thermometers are present on the market, allowing continuous monitoring and comfort. Examples of such devices are the iFever, iTherm and Tadsafe™ wrist thermometers, all equipped with Bluetooth connectivity, remotely monitoring the patients' temperature, suitable for infants (iFever, 2018; Indiegogo, 2018; TADSAFE, 2019). Conversely, the plaster-type thermometers represent a practical solution for continuously detecting neonates' body temperature without the staff intervention for carrying the measure. Fever Scout (Figure 3a), TempTraq (Figure 3b), and Tucky (Figure 3c) are examples of these devices, representing hand-free, easy-of-use, and reusable solutions to monitor body temperature (VivaLNK, 2020; E-takescare, 2021; TempTraq, 2021).

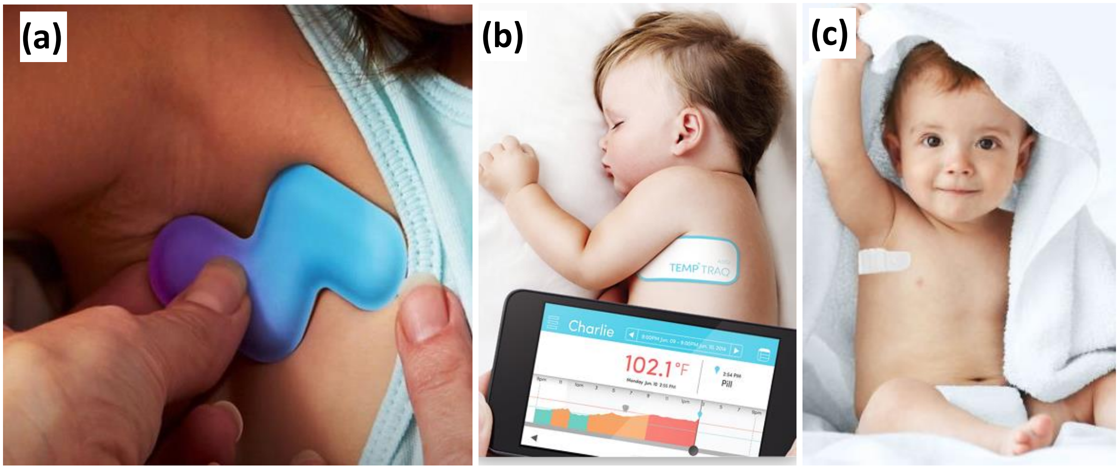


Figure 3. Example of plaster-type thermometers: Fever Scout device, manufactured by Vivalnk Co.(a) (VivaLNK 2020); TempTraq thermometer, manufactured by Blue Spark Technologies, Inc.(b) (E-takescare 2021); and Tucky wearable thermometer, produced by E-takescare Co (c) (TempTraq 2021).

Besides, impaired respiratory activity induced by the COVID-19 affects significantly also cardiovascular activity. Thus, the heart rate (HR) represents a good indicator of the body's physiological stress caused by the viral infection. Wearable devices constitute an effective, convenient, and handful solution for monitoring the HR of COVID-19 patients. In (Patil *et al.*, 2019), the authors developed a wireless device to continuously monitor heart activity. The system acquires and processes the data from a photoplethysmography (PPG) sensor and sends SMSs (short message service) to medical staff and parents for quick rescue. Furthermore, P. Sharma *et al.* introduced a novel acoustic sensing method for cardiac monitoring in wearable devices. The technique is based on detecting the heart sounds and the pulse waves from the wrist's radial artery (Sharma *et al.*, 2019). Also, in (Shahshahani *et al.*, 2017), the authors have introduced a non-invasive ultrasound technology to detect the heart motions and, thus, extracts the heart rate. The developed wearable prototype detects the time-of-flight (TOF) and amplitude of ultrasound signal reflected from the chest. Furthermore, in (Quy *et al.*, 2019), the authors proposed a wrist-type wearable device to monitor the heart rate based on highly sensitive and ultrastable piezoresistive pressure sensors. This last includes a multi-layer structure of graphite/polydimethylsiloxane composite.

Since the main consequence of the COVID-19 virus is bilateral pneumonia which compromises the respiratory capacity of the infected patient, the monitoring of blood oxygenation (SpO_2) is the primary indicator for establishing acuity and advancement of COVID-19 disease. In (Xue *et al.*, 2015), the authors developed a wearable device to continuously monitor SpO_2 and temperature. The system includes an AFE44x0 chip for implementing the pulse-oximeter, with the sensing probe applied to the earlobes. Besides, in (Son *et al.*, 2017), the authors use a wearable device for SpO2 measurement to monitor the user's health condition in real-time. The developed sensing unit is based on the reflective PPG principle, detecting by a photodiode the reflected light emitted by infrared and red LEDs (light-emitting diodes).

Similarly, R. R. Adiputra et al. developed a low-power and low-cost device to monitor SpO_2 and HR (Adiputra *et al.*, 2018). Acquired data are wirelessly transmitted, by network gateway, IoT application, where the data are displayed, stored and analyzed. Also, Q. Chen *et al.* developed a wearable system to monitor the blood oxygenation from the PPG signal proposing a new adaptive cancellation algorithm based on adaptive filtering to delete motion-induced interference (Chen and Tang, 2020).

The respiration rate (RR) is another fundamental indicator for establishing a user's health status and can suggest the onset of respiration disease, as COVID-19. M. Chu *et al.* developed a disposable respiration sensor with a form factor of a typical patch and including a strain gage which converts the movements of the chest due to breathing into a resistance variation, processed to extract the RR data (Chu *et al.*, 2019). The RR can be estimated from the acceleration data acquired by a wearable device. In ref. (Hung, 2017), the authors demonstrated that chest-acceleration data could provide a reliable estimation of the waveform and the respiration rate. This method could detect some respiration disease, such as obtrusive apnea. In (Jafari Tadi *et al.*, 2014), the authors present a seismocardiograph (SCG) method based on accelerometer data for determining both the RR and information related to the rest phase during the cardiac cycle obtained from myocardial movements (atrial and ventricular). The obtained results demonstrated a high linear correlation between the derived measures of RR and myocardial movements with reference ones acquired by an ECG (electrocardiogram) and respiration belt. A research group of Cambridge's Dept. of Engineering small conductive fibres realized by 3D printing to sense the breathing in tridimensional modality (Wang *et al.*, 2020) (Figure 4); the corresponding process is called inflight fibre printing (iFP). The researchers have developed a micro-scale 3D printed composite fibres constituted by a silver core covered by a thin film of conductive polymers (PEDOT:PSS [poly(3,4-ethylenedioxythiophene). These sensors are lightweight, cheap, small, and can be easily integrated into the fabric. Since the fibres are fully biocompatible and with dimensions compatible with the biological cells, they can deploy biological cells. Alternatively, RR can be assessed by monitoring body temperature variations, humidity, and CO_2 using wearable devices (Liu *et al.*, 2019). Besides, the RR can be determined from the respiratory airflow detected acoustic transducers (microphone) applied in different areas of the human body, such as mouth, nose, and the ear canal.

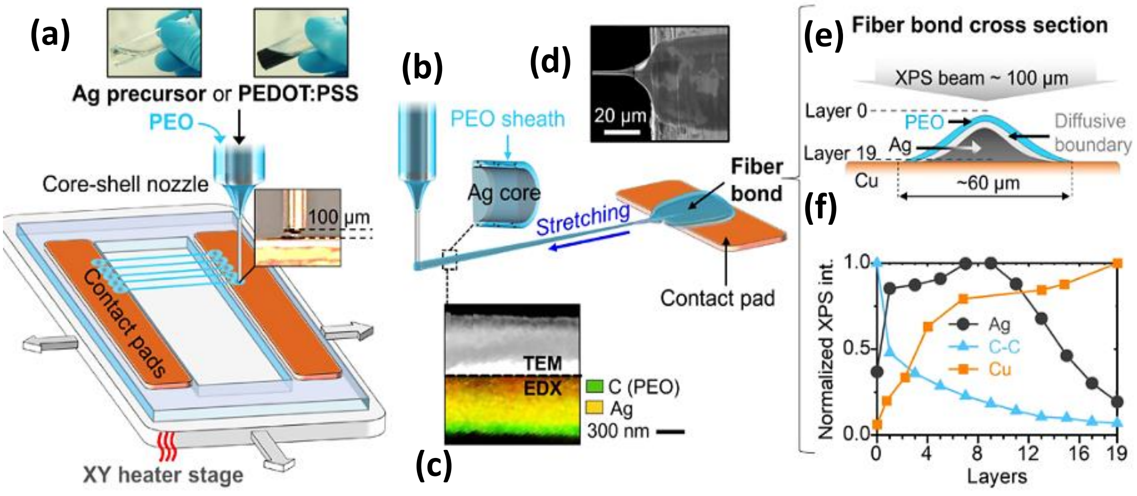


Figure 4. Schematic representation of the iFP process (a); Schematic view of the iFP fibres' deposition (b), Transmission Electron Microscope (TEM) and Electron Diffraction Spectroscopy (EDX) image of a single iFP fibre (c); Scanning electron microscopy (SEM) image depicting fibre bond with a contact pad (d) and related cross-section (e); XPS (X-ray photoelectron spectroscopy) profiling on the Ag fibre bond (f) (Wang *et al.*, 2020).

Also, *PMD Solutions* has proposed the *RespiraSense*, a wearable device that continuously monitors the respiration rate, showing high tolerance to the user's motion (PMD Solutions, 2021). The device uses piezoelectric thin-film sensors arranged into an array to measure deformation and angles of the abdominal wall, occurring during respiration and converting them into an electrical signal. The RespiraSense detects the sensors' signals and determines the mean respiration rate over 15 minutes time interval through a proprietary algorithm, discarding the no significant data. Comparing the measures provided by the device with those of the Capnography system, the experimental results demonstrated a 95% confidence level between ±2%, confirming the accuracy of the device in the considered RR range (i.e. 9÷21 BPM-breaths per minute).

Also, the data provided by an ordinary smartwatch can be used to detect preliminary symptoms of the COVID-19 disease. Specifically, in (Mishra *et al.*, 2020), the authors have presented a smartphone app that collects the smartphone and activity tracker data, along with self-reported information and diagnostic tests results, to identify which symptoms are distinctive of COVID-19 disease onset. They have demonstrated that considering a combination of sensor and self-provided data, the developed model produce an area under the curve (AUC) equal to 0.8 in discerning positive from negative symptomatic patients, more performant than the model just considering the symptoms (AUC=0.71; IRQ=0.63-0.79-impulsive relapse questionnaire). The performances of these techniques can be improved by collecting data from other low-cost multifunctional wearable devices. Also, the availability of innovative sensors like wristband, tattoo, textiles, patches, and ring can aid to detect biophysical and environmental parameters. For instance, R. Moreddu *et al.* developed a contact lens sensor to detect analytes (i.e. glucose, proteins, nitrite ions, etc.) into the tears for monitoring the ocular health both in clinics and at point-of-care settings (Moreddu *et al.*, 2020). The lens includes microfluidic channels in the form of a ring and four lateral branches realized by laser ablation and biosensors placed in the branch ends. The experimental tests, carried out using synthetic tears and colourimetric detection by a Matlab algorithm executed by a smartphone, demonstrated rapid and accurate detection of considered analytes. Besides, an efficient and practical solution for monitoring the blood glucose level are the smart tattoos implanted under the skin. These last are composed of an array of biosensors implanted inside the subcutaneous tissue detecting the local glucose change in the interstitial fluid (Meetoo *et al.*, 2019). If the glucose level overcomes a determined threshold, colour changes are produced and detectable by non-invasively using an optical reader; these technologies can be easily extended to detect other analytes, like the COVID-19 virus. Also, in (Mojsoska *et al.*, 2021), the authors have proposed a proof-of-concept of a patch-based COVID-19 assay to detect the SARS-CoV-2 spike surface protein. The patch is based on a graphene working electrode engineered with the anti-body of the spike protein; the variation of cyclic voltammogram of ferri/ferrocyanide solution after the spike protein-antibody binding is ascribable to a change of current in $[Fe(CN)6]3^{-}/4^{-}$ increasing the spike protein concentration. The experimental tests demonstrated that the sensor is featured by a limit of detection of 260 nM.

In the ref. (Jeong *et al.*, 2020), the authors described a tracking and monitoring device developed by researchers at Northwestern University and Chicago’s Shirley Ryan AbilityLab. They proposed a soft, flexible, wirelessly connected, and thin wearable device with the size of a postage stamp placed just below the suprasternal notch (Figure 5). The device produces continuous streams of data and uses artificial intelligence to discover life-saving information and track patients. Precisely, it continuously measures and analyses cough and chest movements (which indicate laboured or irregular breathing), breath sounds, heart rate, and body temperature (including fever) in ways that are impossible for the traditional monitoring systems.

Figure 5. Demonstration of application of the device on the skin (Jeong *et al.*, 2020).

Afterwards, it transmits the data wirelessly to a health insurance portability and accountability act (HIPAA) - protected cloud, where computer algorithms produce custom graphical summaries to make the monitoring even more immediate and easy.

An Australian's Central Queensland University team has used a WHOOP wristwatch to detect the early warning signs of COVID-19 (Labs 2020; Miller *et al.*, 2020). Specifically, the team have analyzed the RR changes to establish the risk of COVID-19 infections and developed a model to determine the probability of positivity to COVID-19 as a function of the respiration rate during sleep. The experimental tests have demonstrated that the proposed model can identify 80% of COVID-19 positive users after a two-day training phase. Also, S. Hassantabar *et al.* have proposed a framework, called CovidDeep, that uses a deep neural network to the data provided by commercial wearable devices to determine the COVID-19 positive cases (Hassantabar *et al.*, 2020). The data were provided by both wearable devices and questionnaires compiled by the user available on a suitable smartphone application. The deep neural network (DNN) has been trained with data collected by 87 people, achieving 98.1% accuracy in discerning COVID-19 positive cases. Besides, N. El-Rashidy *et al.* introduced a fog network framework to fill the gap between medical technologies and the healthcare system to detect users affected by COVID-19 disease (El-Rashidy *et al.*, 2020). The proposed architecture integrates wearable devices, cloud computing, fog computing, and clinical decision support systems to obtain an efficient model to identify infected individuals. The authors have developed a classifier based on a deep convolutional neural network (CNN) applied to X-rays of the chest to identify the patient as infected or normal by assigning weights to the different aspects/features induced by the COVID-19 disease on the lungs. The proposed end-to-end framework allows real-time monitoring of the patient at home, and early detection of infected individuals, tracking their contacts for broking the contagion chain.

The wearable solutions for remotely monitoring the user's biophysical condition are receiving great attention from the scientific community and companies in the period of the COVID-19 Pandemic since they allow to move the no critical patient away from the hospital facilities ensuring a satisfactory level of assistance (Figure 6a). In this field, LifeSignals Co. has developed a single-use biosensor for the COVID-19 pandemic to monitor the patients' main vital signs (Lifesignals, 2020). The device has to be applied to the user's chest and detect movement, heart's electrical activity with a two-channel ECG, blood oxygenation, and pressure (BP); the smart patch is water-proof, resilient and lightweight, feature essential considered the application. Acquired data are wirelessly transmitted, through a gateway, towards a cloud platform where the data are displayed and analyzed for the different monitored patients. Deterioration of respiration or heart parameters trigger an alert, allowing early intervention of the medical staff.

Also, Celsium company presented a wearable thermometer, placed at the armpit, to remotely monitor the user temperature (Celsium, 2020); The device is Bluetooth-connected with a mobile app, synchronized with an intelligent platform, integrating a custom algorithm determining the body temperature accurately. The smart thermometer is aimed for hospital environments, where multiple devices are connected to a central dashboard, allowing the medical operators to monitor the temperature of numerous patients and in real-time. The dashboard warns the medical staff if the temperature overcomes a set threshold over a short time interval (Figure 6b).

Figure 6. Smart patch developed by LifeSignals Co.for monitoring the patients' main vital signs (a); wearable thermometer armpit-placed, produced by Celsium company, placed at the armpit, to monitor the user temperature remotely (b) (Celsium, 2020).

Another wearable device for monitoring and tracking the patient's health conditions is the ECGalert (ECG Alert, 2020) (Figure 7a). It can automatically detect atrial fibrillation in COVID-19 patients, usually from some particular treatment types, like those with hydroxychloroquine and azithromycin. Automatic and early detection is of paramount importance in these cases so the doctors can administer timely treatments. The Oura smart-ring continuously monitors the body temperature, allowing early detection of COVID-19 cases, leading to earlier insolation and testing curbing spread of the infectious disease (Oura, 2020) (Figure 7b). Oura Ring does not use the classic green LED light sensors for heart rate measurement but uses infrared LED technology based on photoplethysmography, capable of detecting volumetric changes in the peripheral blood (therefore from an artery in the palm of the fingers).

Figure 7. ECGalert wearable device (ECG Alert, 2020) (a) and Oura smart-ring (b) monitor and track the patient's health conditions (Oura, 2020).

Another significant value that is monitored is the HRV. Not everyone is aware of this value, but it is essential to describe a person's state of stress or well-being. Heart rate variability is closely related to the autonomic nervous system, and its variation can be fundamental for the proper functioning of the parasympathetic system. A low HRV indicates a low reactivity of the parasympathetic system and a longer recovery from physical and emotional exertion. Cognet Things Company proposes the COVID-19 Tracker, a smart wearable device with multi-faceted solutions for Covid-19 Tracking and Tracing, to improve patient safety and provide actionable insights. The device allows real-time warnings, monitoring, and incident reporting, essential to monitor COVID-19 patients and location tracking and tracing with Geo-fencing. The COVID-19 Patient Tracker automatically detect temperature, heart rate, blood oxygen saturation automatically

The 8 West company has proposed the COVID-19 remote early warning (CREW) to aid the healthcare staff who works on the frontline (8 West, 2020). The CREW system includes:

- A wearable digital thermometer sensor for detecting the body temperature;
- A sensor platform, e.g. smartphone, smartwatch or wearable IoT device running the CREW app.
- A cloud-based server running the CREW system which monitors the incoming data and generates automatic alarms if temperature thresholds are breached.

The CREW system regularly acquires the body temperature and triggers alerts if a temperature threshold has been breached. The system is called CREW, and it consists of sensors, smart devices and a cloud-based monitoring and alerting system. The system has been tested by the medical staff of the Emergency Department of Cork University Hospital (CUH). By integrating wearable technologies and collecting the data from different sensors into an intelligent and scalable monitoring solution, we believe a solution can reassure front line healthcare workers and provide useful data to hospitals and treatment centres related to their valued staff (Figure 8).

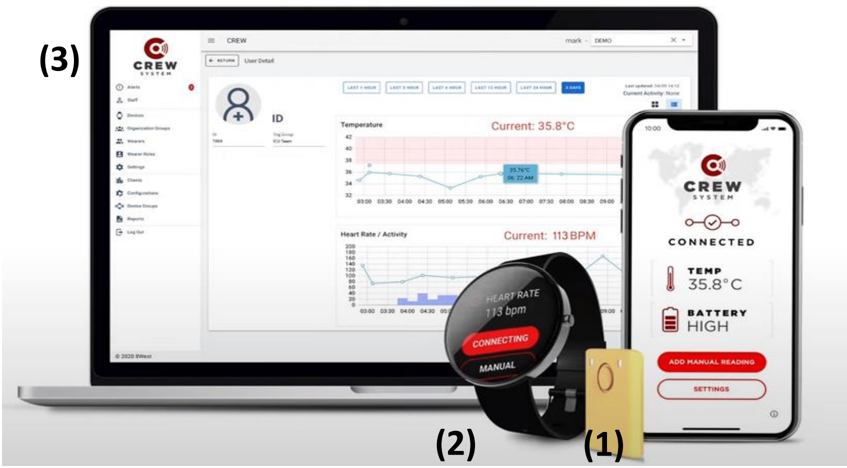


Figure 8. Overview of the main components included in the CREW system: wearable digital thermometer sensor (1), sensor platform (2), and cloud platform (3) (8 West, 2020).

The Vital Patch, manufactured by MediBioSense, is a wearable device for remotely monitoring the health condition of the patient who wears it (VitalConnect, 2020) (Figure 9a). The device detects in real-time eight biophysical parameters (such as body temperature, heart rate, heart-rate variability (HRV), body posture, respiration rate, RR, single ECG, fall-detection, activity level), and wirelessly transmits the acquired information to the patient monitoring platform for storage and analysis. The self-isolation and social distancing featuring the COVID-19 pandemic are inducing several psychological problems, like high-stress level, anxiety, panic attacks, which are just as insidious as the consequences of the virus. The Lief Therapeutics company proposed a wearable device, called Lief Rx, to monitor heart rate and HRV to extract information about the psychophysical conditions, providing biofeedback to the user to reduce their anxiety stress (Lief Therapeutics, 2019). Similarly, Skiin company presented a wide range of garments (underwear, bras, shirts, and sleep masks) equipped with several sensors to continuously monitor vital signs, like sleep quality, activity, temperature, and ECG levels (Figure 9b).

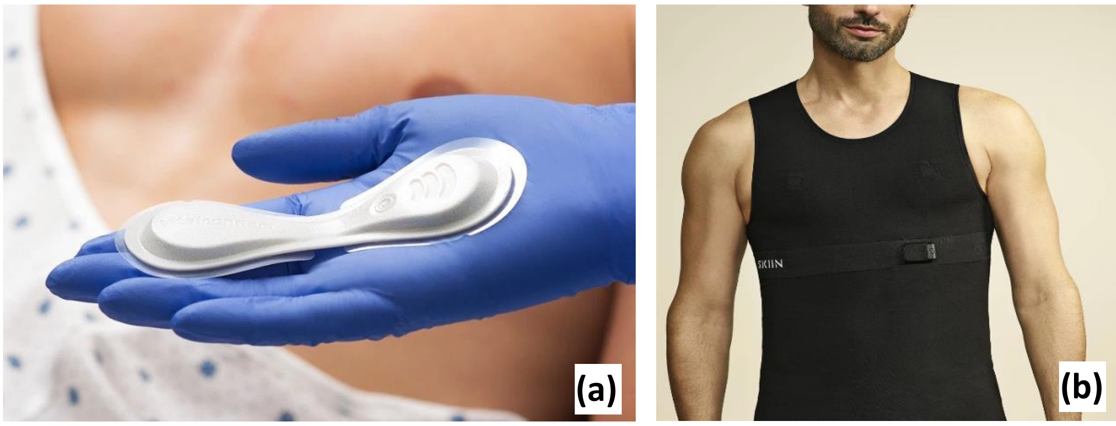


Figure 9. Vital Patch, manufactured by MediBioSense Co., monitors the biophysical parameters (VitalConnect, 2020) (a) and smart garment, produced by Skiin, with different sensors to monitor the user's vital signs (b) (Lief Therapeutics, 2019).

2.1. Overview of innovative masks for limiting the COVID-19 spreading

Currently, several innovative masks have been developed and proposed on the market, able to both perform their filtering function but also detect biophysical parameters. AirPoP Co. patented the Active+ Halo mask constituted by a flexible filtering membrane that adapts to the user's face ensuring a 99.3% particle filtration efficiency (PFE) and 99.9% bacterial filtration efficiency (BFE) (AirPoP Co., 2020). The innovative mask integrates a sensor array to detect the breath parameters and send them to a mobile app, and an onboard LED signals the breath rate. Also, LG Group is developing the PuriCare Wearable Air, a smart mask equipped with two high-performance filters capturing up to 99.5% of virus, bacteria and particles (Figure 10a) (LG Group, 2020). Thanks to a double fan and a RR sensor, the smart mask provides fresh and purified air to the user, whereas the sensor detects all the phases of the respiration rate and the respiration volume, regulating the fan speed accordingly. The fan speed automatically accelerates for supporting the air inhalation and decelerates to reduce the resistance during the expiration. Besides, the mask case includes a wireless recharging system and UV (ultraviolet) LEDs for eliminating germs and viruses.

Similarly, Razer has created the project Hazel, a smart mask ensuring N95 medical-grade respiration protection (Figure 10b) (Razer, 2020). It includes an active ventilation system adjusting incoming airflow as a function of the respiration parameters detected by a built-in microphone and speaker, also used by the mask to understand when the user wears the mask. Also, in this case, a cover is equipped with a wireless recharging system and UV lamp for the auto-sterilization function to kills bacteria and viruses. Also, a research team of the University of Leicester developed a 3D printed face mask, achievable in just 30 minutes, thus suitable for mass production. It must be printed using Copper3D filament, viz a PLA (polylactic acid) filament loaded with copper NPs (nanoparticles), which made the mask antimicrobial, antiviral, reusable and eco-sustainable (NanoHack 3D, 2020).

Figure 10. PuriCare Wearable Air smart mask developed by LG Group (LG Group, 2020) (a); smart mask manufactured by Razer and equipped by an automatic ventilation system (Razer, 2020) (b).

Furthermore, Xiaomi has presented a patent request for the so-called Xiaomi Purely Mask equipped with several sensors for monitoring the respiration status in real-time (Xiaomi, 2020) (Figure 11a). Thanks to the integrated sensors, the mask measures the amount of the absorbed pollutant, air quality index (AQI), respiration rate and the user's movement using integrated accelerometers and gyroscopes to determine variations of the lung capacity. The acquired data are preprocessed by an onboard processing unit and then transmitted to a suitable mobile application where the data are displayed, processed and stored.

The Guardian G-Volt mask, produced by LIGC Applications, is a novel graphene-based filter constituted by a laser-induced graphene (LIG) layer and a graphene foam obtained by CO_2 laser cutting technique (Dezeen, 2019; Stanford *et al.*, 2019). The resulting filter can quickly reach a temperature higher than 300°C, exploiting the Joule-heating mechanism, self-sterilizing the mask. The thermal stability and the relatively high surface of the LIG filter make it very efficient in reducing infection in hospital settings. The G-Volt mask is featured by a filtering efficiency for particles over 0.3 µm and 80% for smaller particles (Figure 11b). The mask is periodically connected to a portable power bank; the resulting heating up destroys the bacteria and virus deposited on the surface, allowing its complete sterilization.

Figure 11. Xiaomi Smart Mask, produced by Xiaomi, for monitoring the respiration status in real-time (Xiaomi, 2020) (a); Guardian G-Volt mask, manufactured by LIGC Applications, equipped with a self-sterilizing graphene filter (Dezeen, 2019; Stanford *et al.*, 2019) (b).

A research team of the University of California are developing a wearable sensor applicable to the mask for detecting the presence of the proteases, enzymes that speed up the breakdown of proteins, related to the COVID-19 virus (Labios and Diego, 2020; Yim *et al.*, 2020) (Figure 12a). The sensor includes a small blister and a strip used to colled the proteases present in the exhaled breath. To carry out a test, the user must squeeze the blister taking into contact the NPs with the strip surface, which changes colour in the presence of proteases and thus the COVID-19 virus. Also, Harvard and MIT researchers are developing a face mask to generate a fluorescent emission if a person infected by COVID-19 breathes, coughs, or sneezes. Genetic material as RNA (ribonucleic acid) or DNA (deoxyribonucleic acid) has been deposited by a lyophilizer on the fabric surface, which collects the aqueous particles carrying out the virus without killing them (Figure 12b). The virus binds with the deposited material producing a radiative emission, not visible to the naked eye but quantifiable with a fluorimeter. The proposed solution requires two conditions for the activation, viz the sample’s moisture (saliva, mucus, etc.) and the virus's genetic sequence. In (Rabiee *et al.*, 2020), the authors developed a point-of-use rapid detection of the

COVID-19 virus in the form of a mask coated by metallic NPs doped with an organo-metallic framework; the interaction with the virus changes the optical properties of NPs, resulting in a colour variation of the mask's surface. Besides, the authors propose an overview of the different diagnosing methods and techniques for rapid detection of COVID-19 using optical techniques, exploiting the easy absorption/desorption of the nanostructured materials (i.e. Gold, Silver, Magnetic and metal-organic NPs) (Ghasemi *et al.*, 2015; Rabiee *et al.*, 2020; Nejad *et al.*, 2020). The aim is to develop point-of-care solutions to take over the presence of a virus or even its concentration in the air in a rapid and non-invasive way (de Fazio *et al.*, 2021). Also, in (Giovannini et al. 2021), the authors investigated different techniques and critical technical aspects for detecting virus by analysing the exhaled breath, including electrochemical, chemoresistive, biological gas sensors or the breath's liquid phase (i.e. EBA-exhaled breath aerosol or EBC-exhaled breath condensate) using PCR-based (polymerase chain reaction) detection methods.

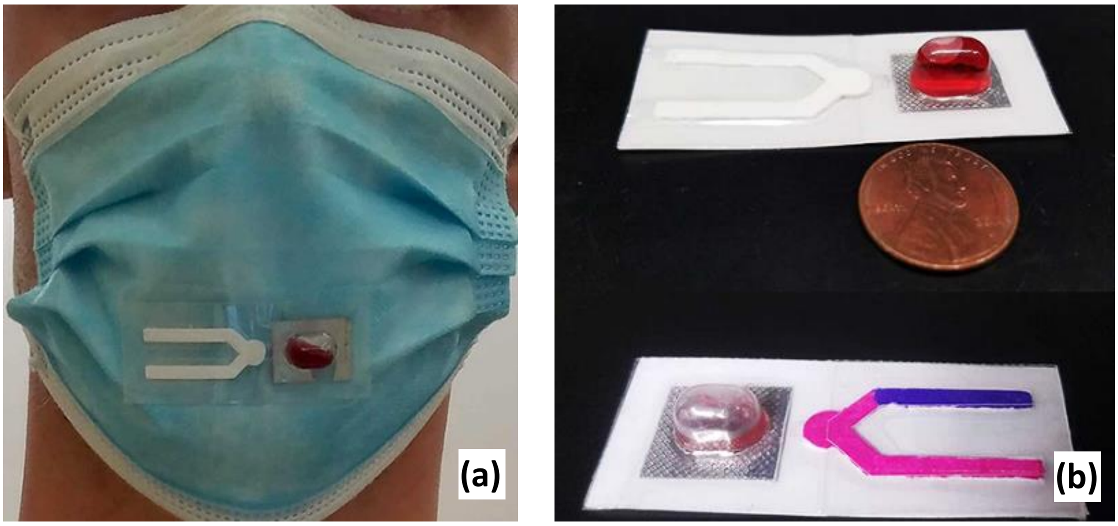


Figure 12. Sensor, developed by the University of California, to detect the presence in the exhaled breath of the proteases related to COVID-19 virus (a); detail of the sensor before the application on the mask (b) (Labios and Diego, 2020; Yim *et al.*, 2020).

2.2. *Study on implantable devices for detecting the effects of COVID-19 disease on the human body*

Recent studies have been aimed to determine the effects of COVID-19 on the human body; in fact, the data suggests a correlation between cardiovascular diseases and COVID-19, also emerging several months after the tested negativity to the virus. Particularly, several infected patients show acute cardiovascular events besides other complications correlated to COVID-19 (Paramasivam *et al.*, 2020; Diller *et al.*, 2020). Cardiac implantable monitoring devices are a smart solution to remotely check the cardiac muscle's integrity and functionality, avoid long hospital stays, better respect a fixed schedule of exams, and rapidly detect the onset of deteriorations in clinical conditions. The COVID-19 pandemic has heavily changed the medical activities inside the hospital; the main prerogative is to reduce the number of individuals accessing the hospital facility for minimizing the contagion risk towards patients and caregivers.

The introduction of remote monitoring of the patient's cardiovascular condition was proposed in (Mabo *et al.*, 2012); the authors report the main results of the COMPASS trial, a randomized trial for long-term remote monitoring of patients with implanted a pacemaker. The Home Monitoring®, produced by Biotronik, has been employed to automatically transmit the data acquired by implantable devices on a secure Internet site, where medical staff analyses the data to determine the patient's status. The COMPASS trial involved 538 patients randomly selected for remotely monitoring follow-up observed for 18.3 months time interval. The authors demonstrated that 62% of cases, a change in pacemaker programming or drug therapy, were done against 29% in the control group. Remote monitoring is a safe and efficient solution for long-term follow-up of permanently paced patients, reducing health care costs and the risk of hospital overcrowding.

Furthermore, H. Versteeg *et al.* analyzed the influence of the remote patient monitoring systems on the outcome of patients' clinical course (Versteeg *et al.*, 2014). The study, called REMOTE-CIED (cardiac implanted electronic device), considers 900 patients affected by cardiac diseases and with an implantable cardioverter-defibrillator, monitored every 3-6 months on a 2-year time interval. The obtained results demonstrated that remote patient monitoring could help to implement a centralized care monitoring system. An increase in intracardiac pressure is the main indicator of the worsening of heart conditions and is crucial for early establishing a rapid intervention, reducing the probability of complications. CardioMEMS HF®, manufactured by Abbott Mabs, is a wireless monitoring platform for detecting variations of pulmonary artery pressure, an indicator of the heart condition (Sandhu *et al.*, 2016). The system allows real-time notification of patient's conditions, secure data analysis and access, as well as tailored management of user's follow-up. The implantable MEMS (micro-electro-mechanical system) device is battery-free but uses the RF technology to acquire and transmit the pulmonary pressure data, exploiting the energy provided by a proprietary electronic monitoring system (Figure 13a).

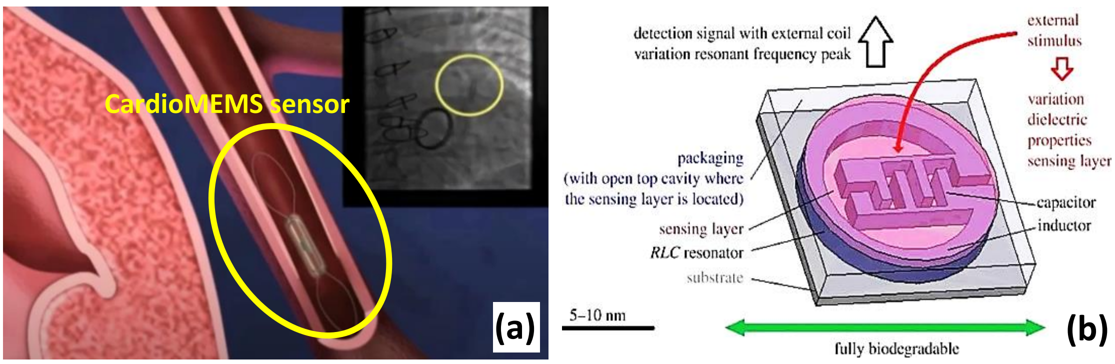


Figure 13. Positioning of the MEMS sensors inside the pulmonary artery branch (a); resonant detection circuit employed by the MEMS sensors to detect the pressure variations (b) (Sandhu *et al.*, 2016).

The sensor included a coil and pressure-sensitive capacitor enclosed into a silica cover and two nitinol loops to hook it up to the pulmonary artery branch (Figure 13b). The capacitance value depends on blood pressure, varying the resonance frequency accordingly; the frequency shift signal is processed by the electronic section for extracting the pressure waveform. The acquired data are then sent to a secure database and available to the medical staff on the CardioMEMS proprietary website. The clinical test was reported in the CHAMPION trial considering 550 HF (i.e. heart failure) individuals and demonstrating a great reduction of the hospitalization time, along with the suitability of the device to monitor in real-time the hemodynamic parameters of the HF patient (Givertz *et al.*, 2017).

Similarly, Endotronix Inc. (Chicago, IL, USA) has developed the Cordella system, suitably designed for HF patients for continuous monitoring of health conditions and remote treatment definition (Mullens *et al.*, 2020). The Cordella system includes an implantable MEMS pressure sensor designed to be placed inside the patients' pulmonary artery (Figure 14a), wirelessly providing real-time data related to the pulmonary artery pressure to a portable reader (Figure 14b). The collected data are then wirelessly transmitted to a cloud platform, where the data are stored and analysed by the company staff.

Furthermore, in (Walton and Krum, 2005), the authors described the HeartPOD system, manufactured by Abbott Inc., to measure the left atrial pressure (LAP); the system is composed of an implantable sensor interfaced with a subcutaneous antenna coil, an elaboration module, and a remote clinical software platform. The sensing section is battery-less but powered by an external telemetry coil and positioned across the inter-atrial septum via trans-septal catheterisation. The elaboration module receives and processes the telemetry data and providing patient feedback about the frequency of blood pressure measurements.

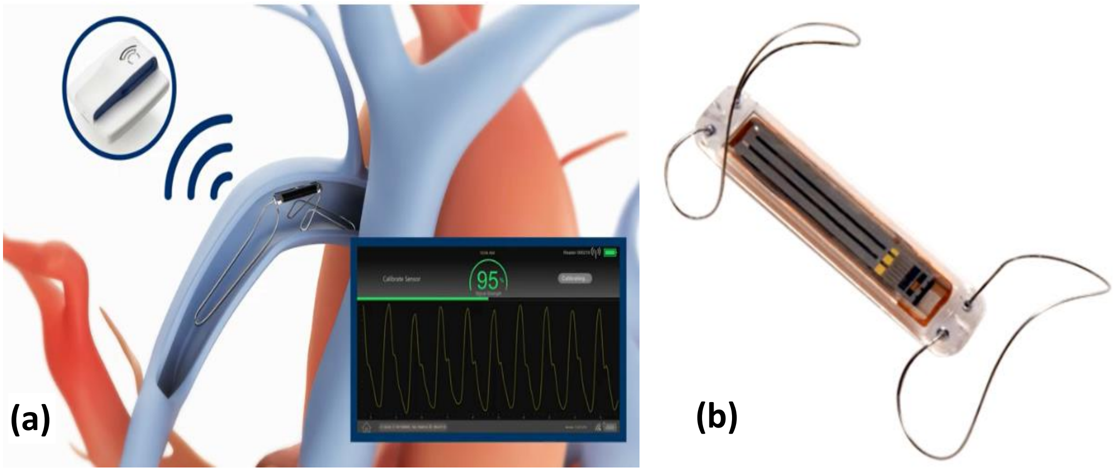


Figure 14. Positioning of the Cordella sensor, produced by Endotronix Inc., inside the pulmonary artery for monitoring the blood pressure (a); detail of the Cordella sensor (b) (Mullens *et al.*, 2020).

Also, the V-LAP™, produced by Vectorious Medical Technologies, is a miniaturized, wireless, and battery-free monitoring system for providing detailed information concerning the LAP (Perl *et al.*, 2019). The implant must be positioned directly on the heart's interatrial septum (Figure 15a) and wirelessly transmitting daily hemodynamic data towards a cloud platform. This last includes three components (Figure 15b):

1) A pressure cup, including the MEMS pressure transducer, positioned in the left atrial side;
2) A sealed tube containing the electronic section and the transmission module;
3) A braided scaffold, made of nitinol, for anchoring the implant to the heart wall.

When opened, the fixing scaffold has an 18 mm diameter on the left atrium and 16 mm on the right atrium, whereas the implant is featured by a maximum diameter of 3.8 mm and a length lower than 18 mm. The system includes an external unit, which power supplies the implant and wirelessly receives the data every day and share the data with the cloud platform (Figure 15c).

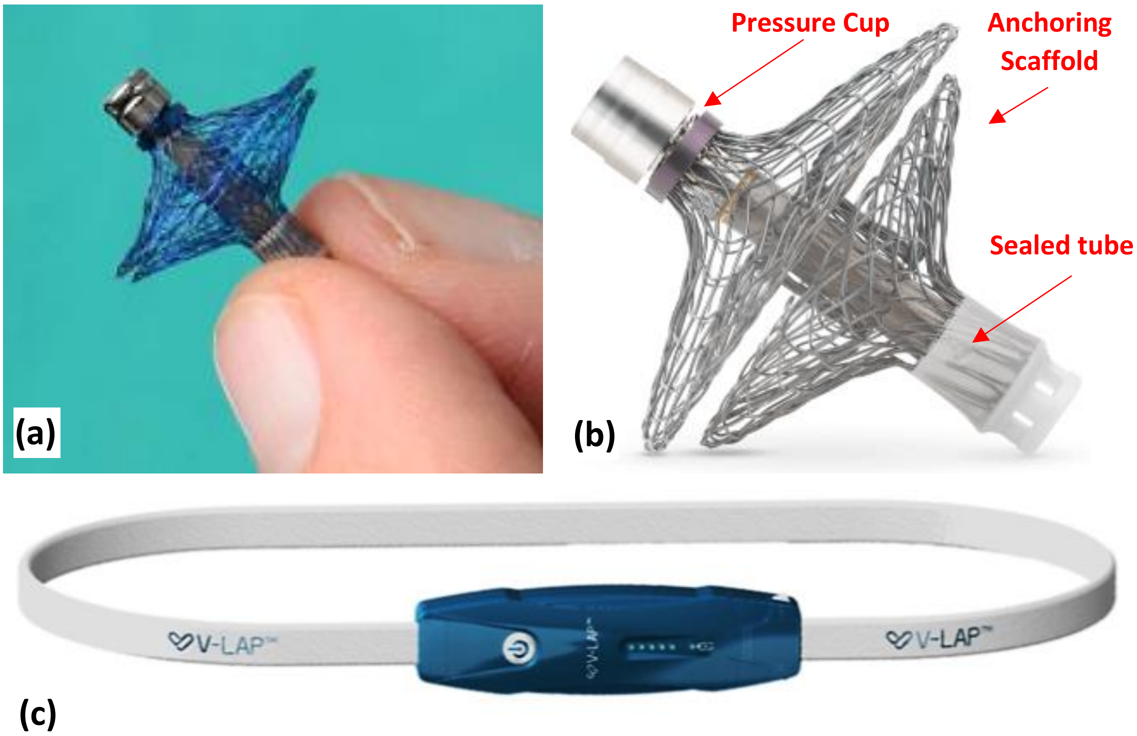


Figure 15. V-LAP™ implant for remotely monitoring the LAP (a); its main sections (b); V-LAP™ external unit (c) (Perl *et al.*, 2019).

3. Overview of Commercial Wearable Solutions For Complying With The Social Distancing Rules

This section investigates the innovative wearable applications for complying with the new measures to contain the COVID-19 pandemic diffusion, especially in terms of social distancing. In particular, with the outbreak of the COVID-19 Pandemic on a global scale, several companies in the electronic design and IoT application have addressed their efforts to develop solutions able to trace the contacts had in the previous weeks the infected users. Several standard communication technologies (BLE-Bluetooth low energy, WiFi, LTE-long term evolution, etc.) are employed to determine the duration and intensity of the social contact using properly defined metrics and keep track of them. Furthermore, several wearable IoT solutions have been proposed on the market to monitor the user biophysical conditions remotely and early detect the symptoms commonly associated with the COVID-19 (cough, shortness of breath, low SpO_2 level) (Larsen *et al.*, 2020; Seshadri *et al.*, 2020; Visconti *et al.*, 2020; Calabrese *et al.*, 2020; de Fazio *et al.*, 2020a; Grant *et al.*, 2020).

Close-to-me device, manufactured by Partitalia Srl, is the device worn by two or more people in the same room, guarantees the "social distance" of one meter (Close-To-Me, 2020). In particular, the device works like this: based on radio frequency technology, generating a radio bubble - low frequency and non-invasive - around the user (Figure 16). When the distancing isn't satisfied, an acoustic sound and a vibration signal that you are less than a meter away. Furthermore, through simple implementations, the device can be used for access control, attendance detection and payment of the company canteen. Close-to-me can be customized and purchased either as a bracelet or as a key ring, thus remaining a non-invasive device, lightweight and almost maintenance-less. It aims to simplify the procedures relating to the reopening of companies since it can be easily implemented quickly.

Figure 16. Graphic representation of the close-to-me system (a); front-view of the wearable to monitor social distancing (Close-To-Me, 2020).

The "Vita" wearable device, on the other hand, is designed for the constant observation of vital parameters in patients treatable by telemedicine, in all cases in which it is considered essential to highlight a possible infection (Partitalia, 2020). The device is equipped with a high-efficiency battery, which lasts more than two weeks. Also, it integrates different sensors for detecting heart rate, oxygen saturation, a fundamental parameter for COVID-19, body temperature and the electrocardiogram. Thanks to these features, the wearable can be used to monitor the biophysical conditions of long-term patients, as well as employees in the workplace.

Furthermore, Safe Spacer ™ is a patent-pending wearable device that helps users keep social distance within safe limits by accurately detecting when other devices are within 2 m radius and warning the user with visual, vibrating or audible alarms (Safe Spacer ™, 2020) (Figure 17a and 17b). Ultra-wideband technology delivers ten times more accuracy than Bluetooth for superior performance, allowing you to safely reopen your workplace and help stop the spread of COVID-19. In addition, the device emits visual, acoustic and vibro warning signals to alert the user of a colleague's presence at a close distance. Safe Spacer can be comfortably worn by users on a bracelet, lanyard or keychain and features a unique identification (ID) tag and built-in memory that allows contact tracing in the event of coronavirus exposure, keeping organizations safe.

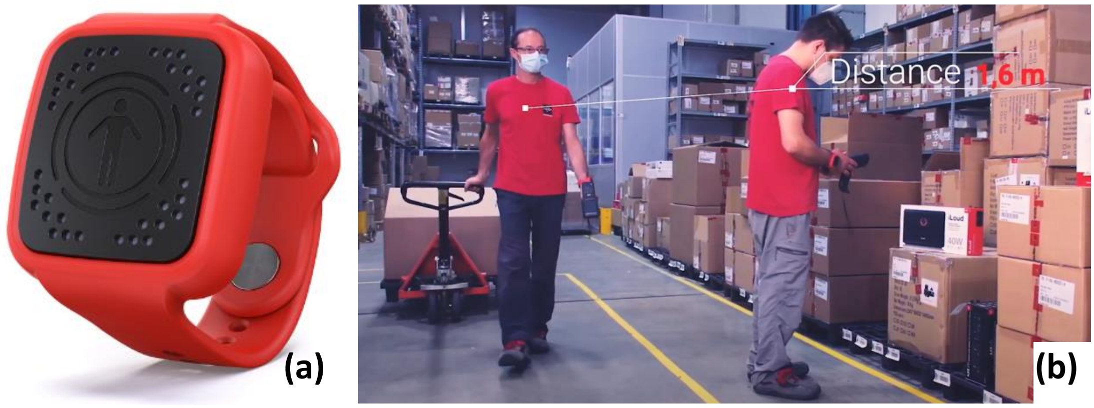


Figure 17. Safe Spacer ™ wearable sensor (a), and an example of an application scenario (b) (Safe Spacer ™, 2020).

Similarly, Abeeway company developed a Smart Badge™ to aid the user in respecting the rules on social distancing in the workplace (Abeeway, 2019). It is lightweight and portable, equipped with sensors supporting multiple geolocation technologies, providing accurate and continuous geolocation data. The device uses the BLE beacon, multi-constellation GNSS (global navigation satellite system)/GPS (global positioning system), low power GPS, WiFi technologies to detect other workers' proximity and evaluate the distance between them. Also, an ultra-low-power LoraWAN (wireless area network) communication module is employed and dynamically manage the localization technology as a function of the operating scenario to optimize the device autonomy (de Fazio *et al.*, 2020b). CrowdLED Inc. has launched the CrowdRanger social distancing wearable devices, based radiofrequency technology to sense when another device is within a set range (Crowdsaver, 2020). If this condition is verified, the device generates a visual, acoustic and vibro warning signal to keep the social distance, increasing the audio volume, warning colour and vibro intensity depending on the distance and contact duration. The alarm stops when the two users move beyond the safety distance. The device records the duration and distance of each contact up to 28 days, allowing the administrator to check the data to identify potentially infected people.

Also, Nymi, Inc. has developed the workplace wearable wristband based on NFC (near field communication) and BLE technology for contact tracing and social-distancing applications (Nymi Inc. 2021). Specifically, the device uses these technologies to determine and quantify social contacts, providing suggestions to the administrators concerning workplace safety. At the end of the day, each wristband sends the acquired information to a central unit to determine potential risks and workers behaviours. The device identifies the user's identity using an integrated fingerprint reader and biometrics parameters to ensure the safety and security of connected workers.

The iFeel-You bracelet is also equipped with sensors to monitor human parameters and warn the user if its body temperature is higher than 37.5°C (Istituto Italiano di Tecnologia, 2020) (Figure 18a). Furthermore, the device monitors, using the Bluetooth frequencies, the distance between peoples detecting the movements and the distance between the bracelets. Once two bracelets are too close, they vibrate and sound, making them aware and ready to keep the safety distance. Similarly, Estimote company, specialized in beacon location devices, used its skills to develop a device to contain the COVID-19 Pandemic (Estimote, 2020) (Figure 18b). They propose a new line of wearable products to monitor the coronavirus pandemic’s potential diffusion between users in the workplace. These devices represent a powerful solution to keep track of any potential contagion between workers and limit the local spreading before becoming uncontrollable. The hardware section consists of a passive GPS receiver and proximity sensors based on Bluetooth and ultra-wide-band radio signals analysis, a rechargeable battery and a built-in LTE transceiver. It also includes a manual control to modify a user’s health conditions, assigning him the states of certified health, symptomatic and verified infected. If the wearer changes his status, indicating possible or verified infection, the system also updates others they’ve been in contact with him depending on proximity and location-data history. The status is also updated in a health dashboard providing detailed logs of possible contacts for centralized management.

Figure 18. iFeel-You bracelet developed by the Italian Institute of Technology (IIT) (Istituto Italiano di Tecnologia, 2020) (a); Line of wearable products, manufactured by Estimote Co., for containing the COVID-19 Pandemic (b) (Estimote, 2020).

4. Tracing Systems for Containing the Covid-19 Pandemic

This paragraph analyzes current technology (including apps, integrated sensors and ad hoc devices) to overcome the problems arising from this Pandemic. The focus is on the various technological approaches we could apply to break down infection and return to everyday life.

Ref. (Immuni, 2020) focuses on the Immuni app. It introduces a new approach to contain the epidemic, starting with COVID-19. The app has a contact tracing feature based on Bluetooth technology. When users discover they have tested positive for the COVID-19 virus, the Immuni notification system allows to anonymously alert people they have been in close contact with and who may also have been infected. By being informed promptly (potentially even before developing symptoms), they can contact their general practitioner (GP) to discuss their situation. It is available for iOS and Android operation systems. The source code was developed by Bending Spoons S.p.A., released under the GNU Affero General Public License version 3. Immuni can determine that a risky exposure has occurred between two users without knowing who those users are and where they met. The app doesn't collect any data that would identify the user, such as their name, date of birth, address, telephone number, or email address. To determine the contact, Immuni uses Bluetooth Low Energy technology (a variant of the standard Bluetooth that uses much less power for communication) and does not use geolocation data of any kind, including GPS data. Immuni has been designed and developed, paying great attention to safeguarding user privacy. The data are collected and managed by the Ministry of Health and stored on servers located in Italy. All data and connections of the app with the server are protected. Also, to ensure that only users who tested positive in the SARS-CoV-2 test could upload their keys to the server, the upload procedure can be performed only in cooperation with an authenticated healthcare provider. The provider asks the user to provide a code generated by the app and inserts it into a back-office tool.

A high-level description of the system is as follows. Once installed and configured on a device (device_A), the app generates a temporary exposure key (randomly generated and changes daily). The app also starts transmitting a BLE signal that contains a proximity identifier (ID_A1, it is assumed fixed for simplicity). When another device (device_B) using the app receives this signal, it registers the ID_A1 locally in his memory. At the same time, device_A records the identifier of device_B (ID_B1, it is also considered fixed). Suppose the user of device_A subsequently tests positive to SARS-CoV-2. In that case, he can upload to the Immuni server the temporary exposure keys. The Immuni app can obtain from the server the recently transmitted proximity identifiers (including ID_A1 of device_A). The device_B checks for new keys uploaded to the server against its local list of identifiers, and if ID_A1 match, the app warns the user of device_B that he may be at risk and provides advice on what to do next (e.g., isolate and call the doctor) (Figure 19).

If the owner of device_B was in proximity to the user of device_A, there is no certainty that he is at risk. Immuni evaluates this risk based on the distance between the two devices and the duration of exposure. This last is estimated from the attenuation of the BLE signal received by device_B. The longer the exposure and the closer the contact, the greater the transmission risk. Generally, an interaction lasting only a couple of minutes and occurring several meters away is considered low risk. But the risk model may evolve as more information on the transmission properties of the SARS-CoV-2 will become available. It should be noted that the distance estimation is affected by different errors. The BLE signal attenuation depends on factors, such as the relative orientation of the two devices and the presence of obstacles (including human bodies). It should be noted that the app has been heavily downloaded and used since it was released (Figure 20).

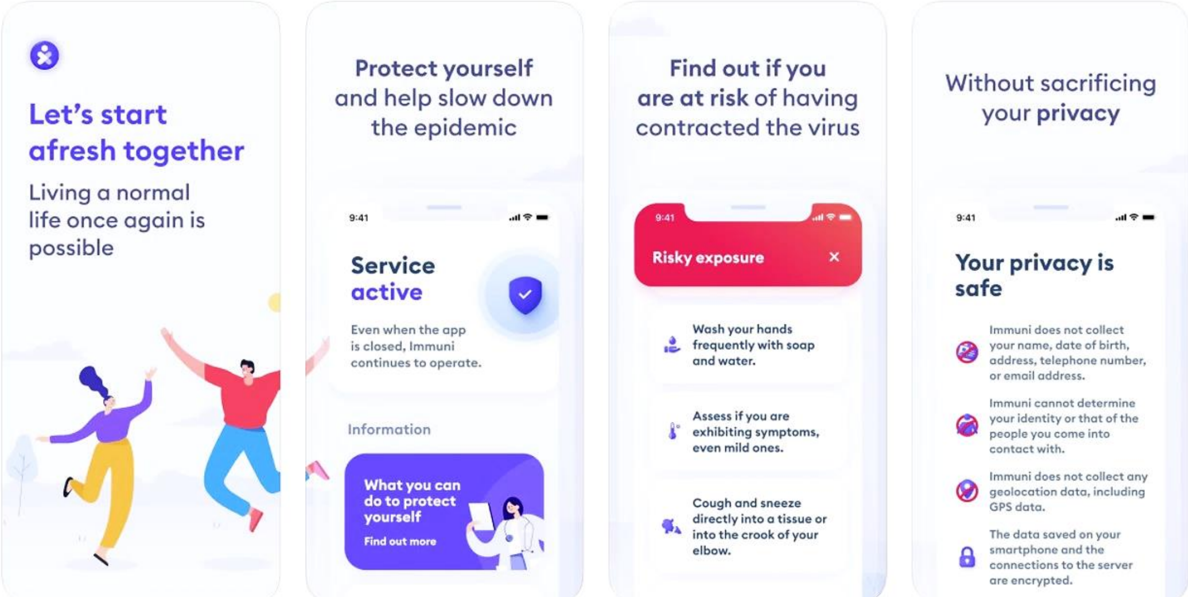


Figure 19. Graphical representation of how the Immuni app works (Immuni,2020).

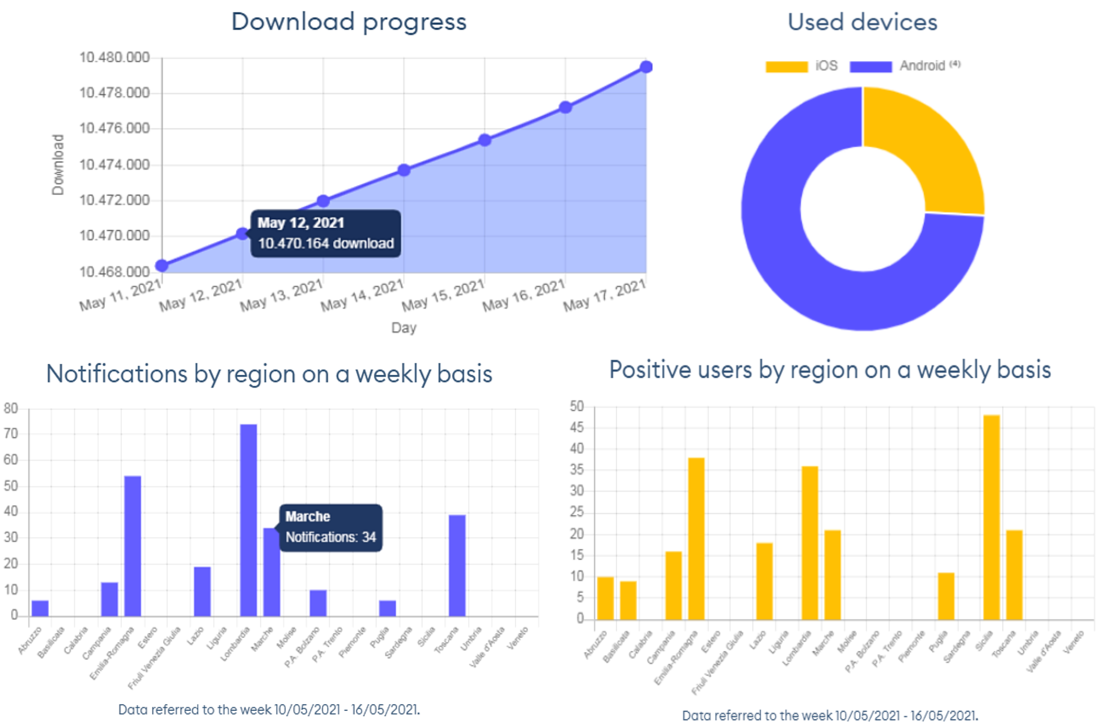


Figure 20. Graphs and histograms reporting some Immuni app statistics (Immuni, 2020).

Wearable and tracking solutions can be used to prevent cross-infection between individuals, providing measures of temperature, heart rate, blood oxygen saturation monitoring, along with real-time positioning information. Singapore was the first country to try to contain the COVID-19 pandemic using a tracing app. TraceTogether Tokens represent an intelligent solution to address COVID-19 using technology (TraceTogether Tokens, 2020). The local authorities declare that the application has received wide popularity quickly, covering 2.1 million people, representing 35% of the population. The system includes wearable devices to support the contact-tracing app for identifying individuals potentially infected by users tested positive to COVID-19 (Figure 21a). The wearable devices allow thousands of vulnerable elderly people who haven't a smartphone to be covered by the tracking system. To each user is assigned a national ID used by the TraceTogether app for the tracking process; if a user is tested positive to COVID-19, they must report their token to local health authorities since they aren't enabled to transmit data over the Internet. The tracking system uses the log data to identify and warn others who might have been infected. The mobile app correlates the verified infected user with those who entered in contact with him. The app uses a time-sensitive ID to determine the user and the relative signal strength indicator (RSSI) readings between the two smartphones to identify the proximity and duration of the contact between two users (Figure 21b).

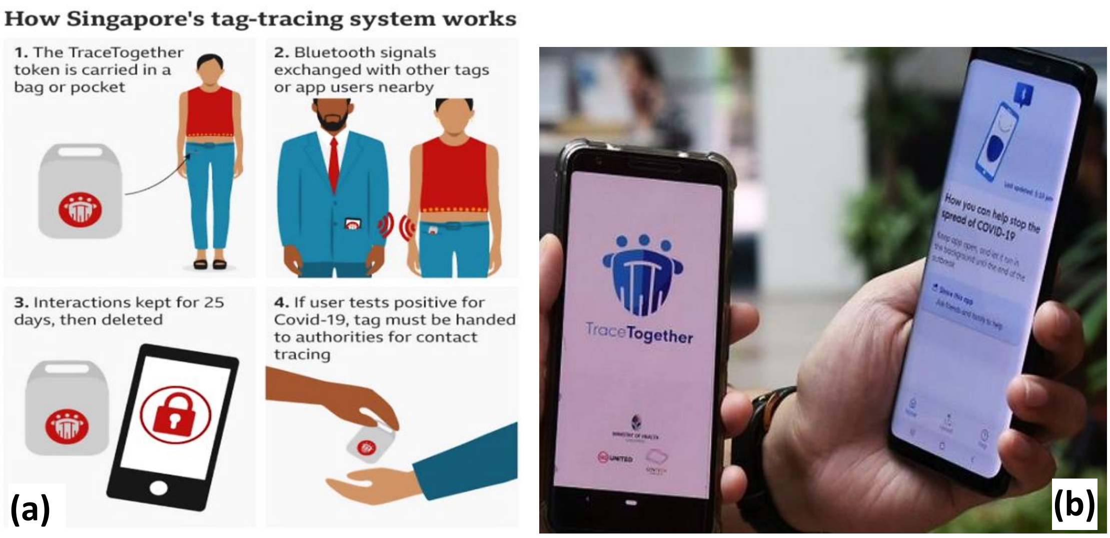


Figure 21. Schematic representation of TraceTogether tracking system (a); mobile application used to support the tracking system (b) (TraceTogether Tokens, 2020).

In the ref. (Simmhan *et al.*, 2020) is presented another contact tracing app, called "GoCoronaGo" (GCG), which exploits the potentiality of BLE technology. The authors developed and analyzed the first experiments with the app's distribution to over 1000 users of the Indian Institute of Science campus in Bangalore. This app uses BLE technology and gives a unique device ID, called contacts, recognized by the other nearby devices with the app scanning. The app stores information on the local device. If a user verifies his positivity to COVID-19, the Bluetooth contacts are uploaded to a central database, and contacts are notified. This mechanism can drastically reduce the time needed to track contacts, slowing the virus spreading.

The main limitation of the Bluetooth technology is the low reliability and asymmetry in detecting nearby users and the low accuracy in distance measurement. The high number of adoptions necessary for contact tracing to be effective leads us to understand why it is still important to use complementary digital contact tracing with manual methods. The proposed app (GCG) for digital tracking aims to solve these limitations. The key feature of the proposed approach is collecting the device contact trace data in a centralized database, regardless of whether the person is diagnosed as positive or negative for COVID-19. The proximity data collected from all app users are used to create a time contact chart. The vertices are devices, and the edges indicate the proximity between devices for a certain period and with given Bluetooth signal strength. According to the World Health Organization (WHO) guidelines, when a user of the GCG app becomes positive for COVID-19, graphical algorithms quickly identify the primary, secondary and other contacts. Also, even if the infected user has lost the Bluetooth connection, the successful scans from other nearby devices can alert the relevant contacts, increasing the detection's reliability. Of course, centralized contact data collection has some drawbacks. Specifically, the privacy implications of tracking interactions. However, the system implements some precautions to try to remedy this inconvenience:

1) the app is designed not on a municipal, regional or national scale but only for distribution within institutions and closed campuses; therefore, the data collected is owned by the host institution and not by a central authority.
2) users are not required to share any personal information, and the devices are identified using a randomly generated ID.

From an architectural perspective, Figure 22 shows a high-level diagram of the developed traceability system.

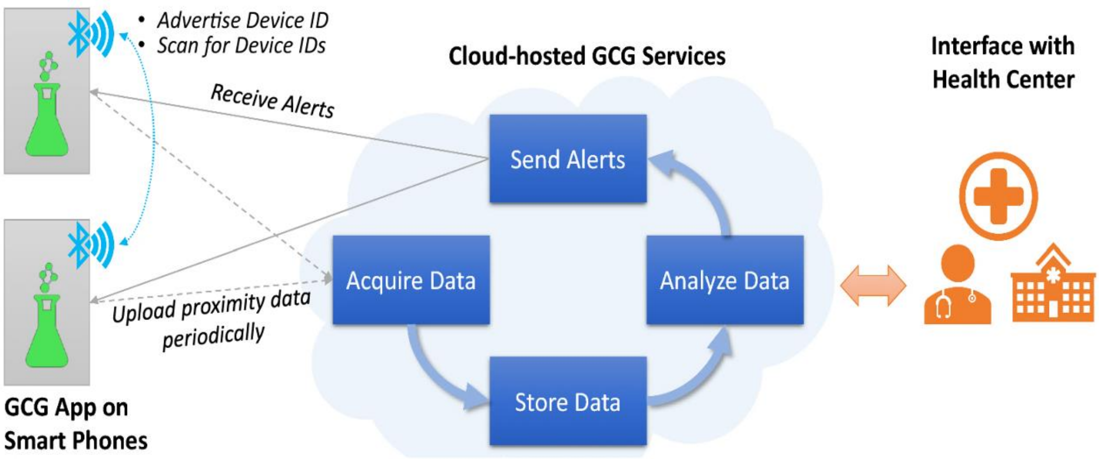


Figure 22. Graphical representation of the architecture of the GoCoronaGo traceability system (Simmhan *et al.*, 2020).

Authorized institution users are provided with individual invitation codes by a separate entity within the institution, typically the IT (information technology) department. The office maintains a mapping from the user's unique invitation code to the actual individual along with their contact details, as shown in Figure 23.

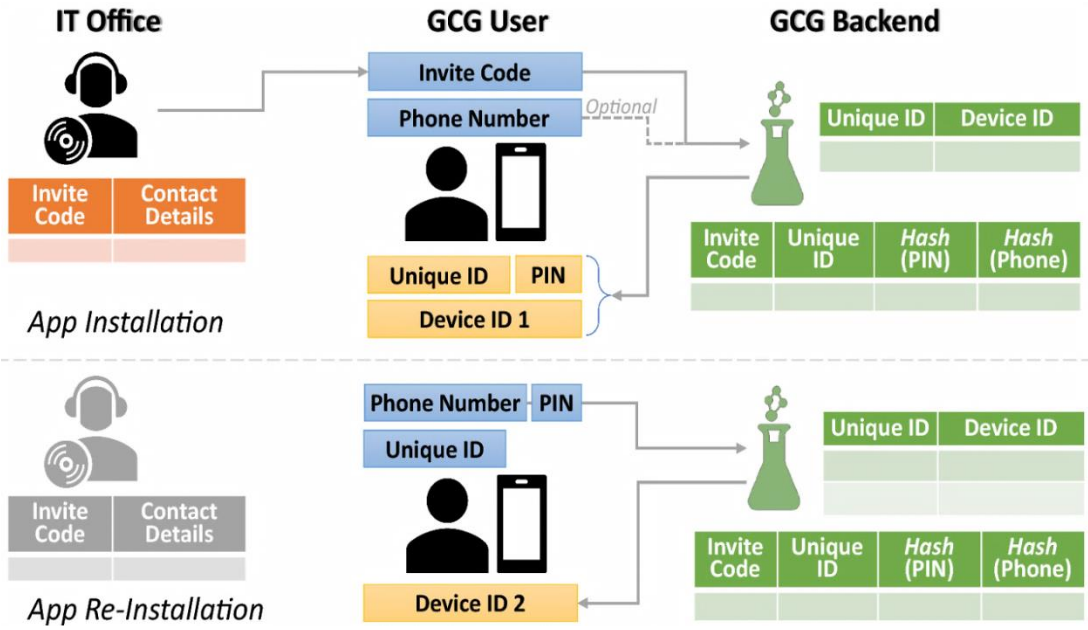
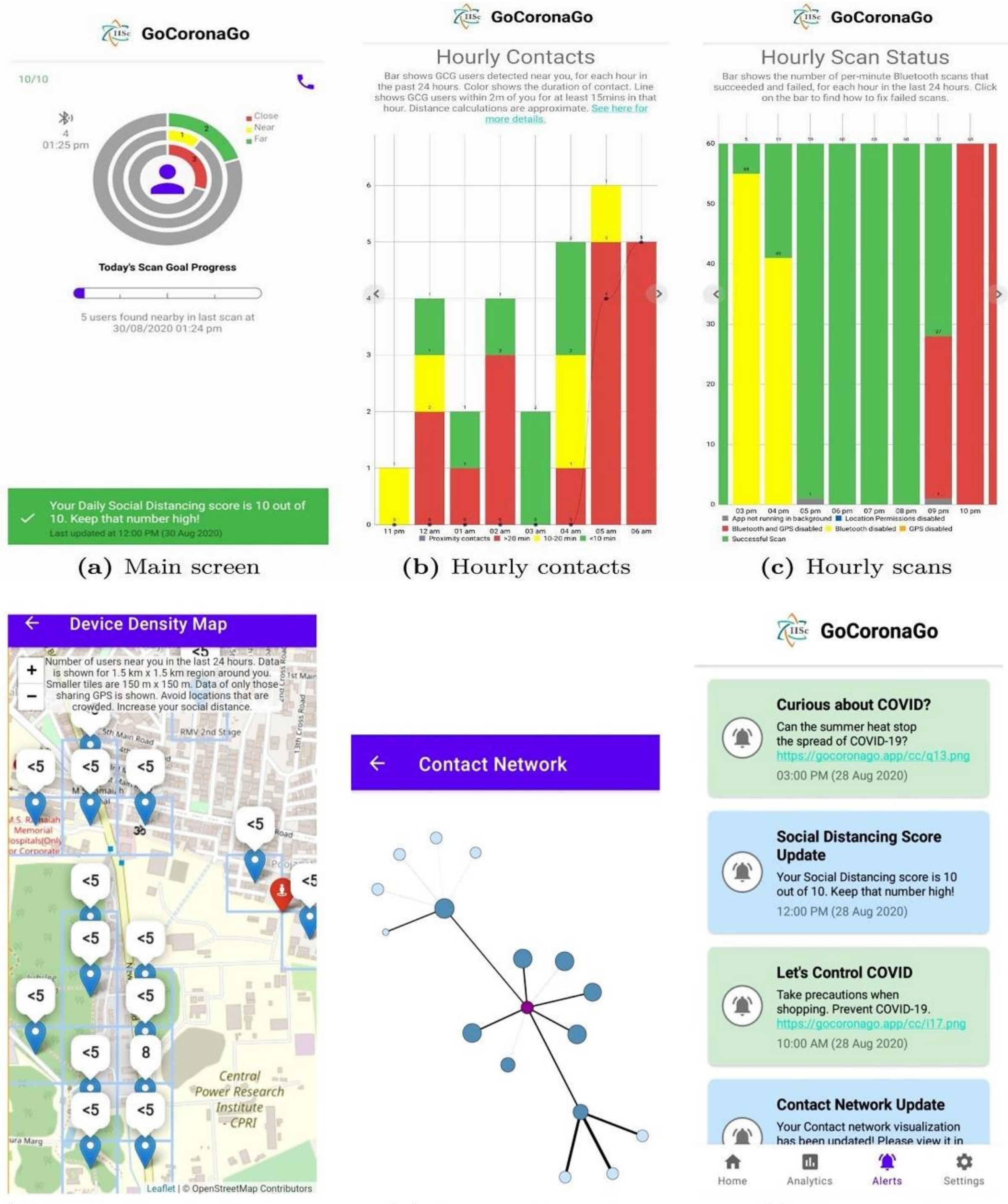


Figure 23. Identifier mapping during GoCoronaGo App installation (Simmhan *et al.*, 2020).

The user can download the GCG App from an institutional link or the Google Play Store. During installation, users enter this invitation code in the app, which validates it with the GCG backend servers and returns a unique user ID, a PIN (personal identification number), along with the device ID. Another required information collected by the app during installation is the operative system version and phone model. This information allows us to know the strength of the Bluetooth signal and translate it into an estimate of the distance. Thus, the GCG app acts as both a client and a server when using BLE scanning and advertising modalities. In addition to tracking Bluetooth contact data, the GCG app offers several functionalities to inform users about COVID-19 and engage them in preventing its spread. Screenshots of these user interface elements are shown in Figures 24.

Unfortunately, COVID-19 disease has many strange long-term symptoms; for example, many symptoms disappear entirely before they suddenly start to worsen, other patients who are declared negative and later are positive again. The high number of strange cases highlights the need for continuous monitoring of patient health. For these reasons, the device proposed in ref. (Jeong *et al.*, 2020) provides round-the-clock monitoring for COVID-19 patients and those exposed to them. The device can monitor hospitalized patients and successively continue supervision at home. The device can monitor the progress of COVID-19 patients, as well as provide early warning signals to frontline workers who are more at risk of contracting this disease.



(a) Main screen (b) Hourly contacts (c) Hourly scans

(d) Device Density Heatmap (e) Contact Network (f) Alerts panel

Figure 24. User interface and analytics in the GCG v0.7 Android App (Simmhan *et al.*, 2020).

In the ref. (Girolami *et al.*, 2020), M. Girolami *et al.* analyzed the wireless BLE signals commonly used by commercial mobile devices. Their work is based on the SocializeME framework, designed to collect proximity information and detect social interactions across personal and heterogeneous mobile devices. The experimental results, obtained by several measurement campaigns on real users, highlighted the technical limitations and qualitative performance of the proposed technique in terms of the received signal strength (RSS), packet loss, channel symmetry for different body position. Specifically, they obtained a dataset with thousands of Bluetooth signals (BLE beacons) collected over 11 hours. The research analyzes the results obtained by the SocializeME Detector (SME)-D algorithm, designed to automatically detect social interactions based on collected wireless signals, achieving an overall accuracy of 81.56% and an F-score of 84.7%. The proposed work aims to design software and analytical tools capable of detecting face-to-face interactions without adopting customized hardware and providing users with a non-invasive technological solution (hardware/software). An essential aspect of this work concerns the SocializeME solution that uses BLE technology, allowing mobile devices to transmit advertising information and capture their intentions.

The first version of the SocializeME app was developed and finalized to advertise the presence of a local device and thus its owner to other devices within a few meters radius and store the information of the received third-party advertising packages. The app presents some drawbacks, namely only the Android devices support background scanning and advertising modes. In contrast, iOS automatically stops advertising and scanning operations while the app switches to the background. Various experimental sessions were conducted to analyze the impact of users' position on signal quality and, consequently, on the correct detection of face-to-face interactions in a completely realistic context. The tests were carried out considering a face-to-face interaction characterized by three different physical distances between the participants:

1. Non-interaction (3 to 3.5m)
2. Approach (3 to 2.5 m)
3. Interaction (2.5 to 1m).

Table 1 summarizes the results of their experimental activity.

Session	#Volunteers	Smartphone models	#Beacons	Duration [min]
1	8	4	53 375	111
2	9	6	87 467	114
3	10	4	205 152	111
4	8	5	198 603	130
5	8	3	247 776	130
6	6	4	27 886	73
Total	–	–	**820 259**	**669**

Table 1. Table summarizing the experimental results reported in (Girolami et al., 2020).

The table shows, for each session, the number of volunteers and of different smartphone models, the number of beacons collected, and the overall duration of the session tests. Then, the duration column provides the average time it took for volunteers to complete a specific session.

Furthermore, a SocializeME framework relies on the analysis of beacon messages collected in their experimental campaign. In detail, the authors used the RSS value experienced by each pair of users involved in an interaction and the beacon loss rate as the main parameters of their algorithm called SocializeME Detector (SME-D). This framework analyzes the time series of beacon messages received by each dyad using a sliding time window of predefined duration (Δ_{up}) and evaluates the following conditions to identify the start time of the social interaction:

• receive at least a given percentage (p%) of the expected beacons;

• the RSS of received beacons is greater or equal to a threshold value T_{rss}.

If the two conditions are met in at least one of the dyad's two directions, social interaction is detected to have started in that time window. Therefore, the interaction is considered active until the closing condition is detected. Namely, the time interval between the last beacon received (with RSS $\geq T_{rss}$) is greater than or equal to Δ_{down}.

In ref. (Ashraf et al., 2020), a smart edge surveillance system is proposed to monitor, alert, and detect the user's heartbeat, body temperature, heart conditions, frequency, and some of the radiological characteristics, for detecting the infected (suspected) persons who use the wearable smart gadgets. Thanks to the proposed framework, a continuously updated map/diagram of the contact chain of people infected with COVID-19 is also determined. Thus, the proposed model helps detect and trace the contagious person and retain the patient data record for analysis.

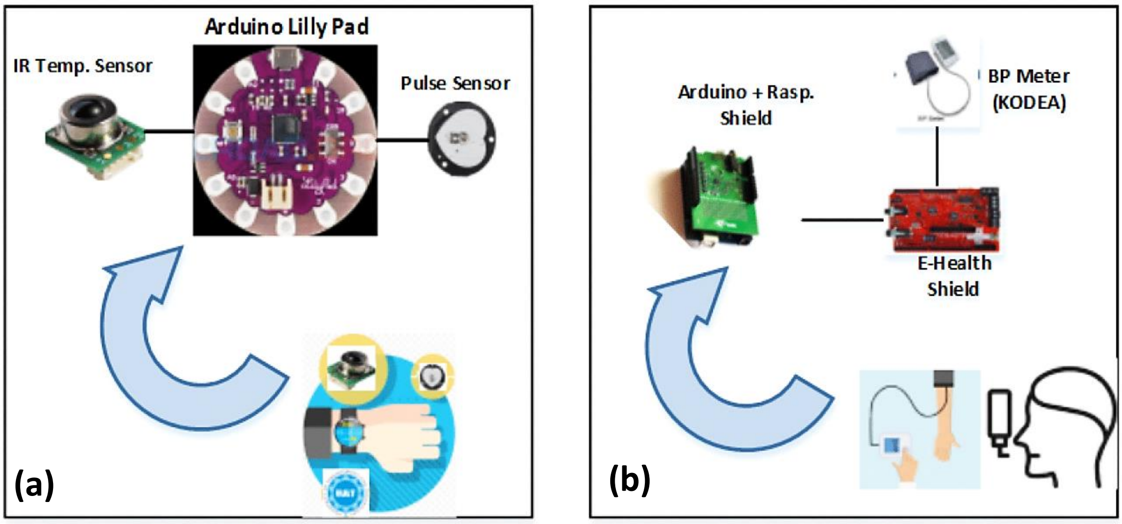


Figure 25. Setup of wearable devices (a) and non-wearable ones (b) (Ashraf *et al.*, 2020).

To collect data, they use two main modules (wearable and non-wearable); the wearable one includes a heart rate and an IR temperature sensor (Figure 25a). The non-wearable module is connected to the file entrance of the airport passage gates or even in shopping malls where large human crowds are expected. According to WHO guidelines, the wearable module provides blood pressure and respiratory data of the suspected victim, to control the infected users (Figure 25b).

This mechanism acquires the values in real-time (from sensors of wearable and non-wearable gadgets) and transmits them to the file *Multi-edge* layer nodes, where the analysis of the suspect's data is carried out. The proposed framework consists of five stages, as evident from the block diagram shown in Figure 26.

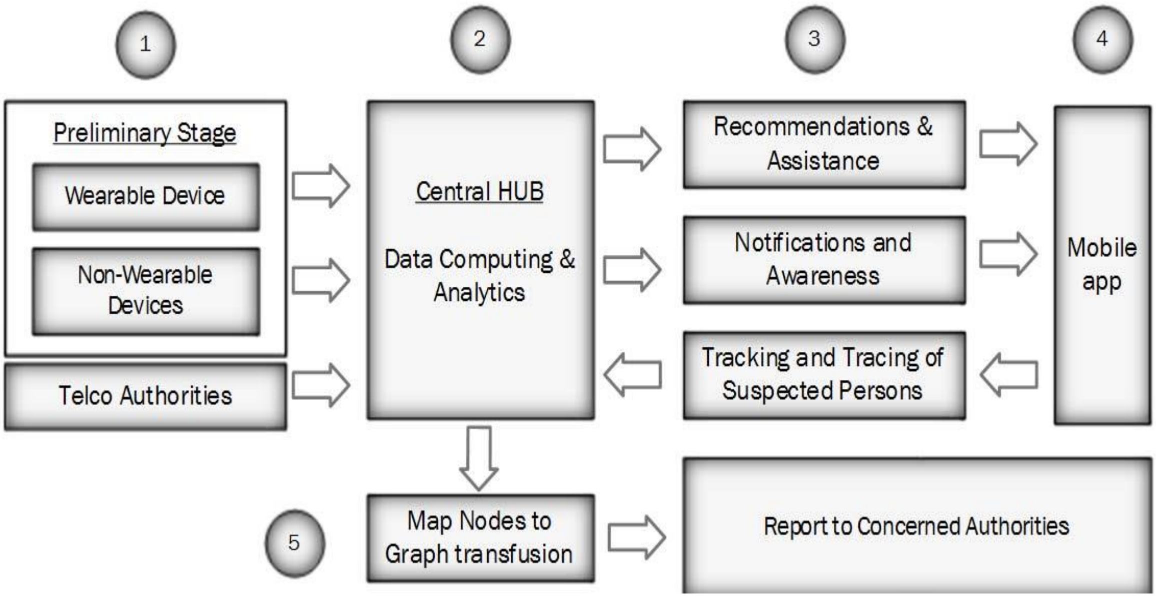


Figure 26. Block Diagram of Proposed System framework (Ashraf *et al.*, 2020).

1. *Preliminary phase*: the data related to the suspected persons is transmitted to the edge and cloud layers.
2. *Central HUB* (data processing and analysis): the data are processed and passed on to the action trigger and graphical mapping unit for nearby alarms and affected authorities.
3. *Action activation*: this stage deals with the transmission of notifications of COVID-19 suspects.
4. *User interface*: this stage interacts with the end-user through an android application.
5. *Graphic display*: this component summarizes the framework's results through a suitable graphical interface, allowing tracking down the suspected COVID-19 nodes (users).

In ref. (Tripathy *et al.*, 2020), an electronic solution, called *EasyBand*, is presented to manage a safe and gradual opening after removing the restrictions imposed to contain the spread of COVID-19. In particular, it is intended to limit new positive cases through automatic contact detection and encourage social distancing. The device includes sensors for detecting nearby similar devices (from 1 to 4 meters), helping citizens stay safe by automatically detecting the suspects. The *EasyBand* electronics consists of specific building blocks such as a power management unit (PMU) to provide adequate DC (direct current) voltage to all the internal blocks and LCD (liquid crystal display) display, a programmable system chip (PSoC), wireless stack, sensors, vibration motors, and I/O units, as shown in Figure 27.

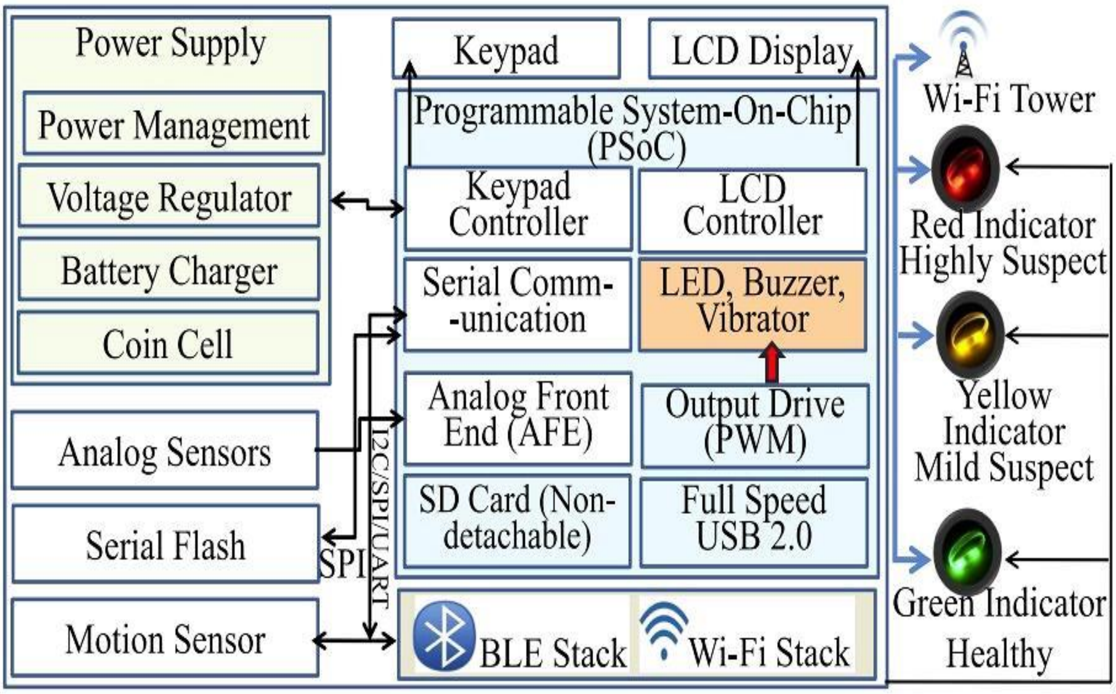


Figure 27. Block diagram of the *EasyBand* system (Tripathy *et al.*, 2020).

The system uses BLE devices to detect the distance between them, whereas the WiFi unit creates the data connection with a city server via a TCP/IP (transmission control protocol/internet protocol) connection. *EasyBand* also has LEDs with three colours, i.e. yellow, green, and red. The green indicator indicates a safe condition, yellow a slightly suspicious, and red a very doubtful. These devices can record information (such as device ID, timestamp, and period) over 15 days and other devices in close contact in the same area. Before removing the lock file from a zone, all people have to be released with an EasyBand with an active green light as the mobility pass. The device also provides a vibrating alert, whether, within 4 meters, a yellow or red device is present. It will beep to provide an even more critical warning if it comes into closer contact with a yellow or red device. If a green device spends a lot of time in close contact with a yellow/red device, its status changes to yellow (Figure 28).

In the ref. (Dong and Yao, 2020) some IoT systems for the user's tracing using GPS receivers (Paek et al. 2010), microphones (Satoh et al. 2013), (Burns et al. 2015), and magnetometers (Jeong *et al.*, 2019) are reported. The most simple method uses GPS technology (based on coordinates) to track users' trajectories and determine the contact distance (Paek *et al.*, 2010). Although it is simply feasible, it is also not optimal due to the high power consumption and low distance resolutions.

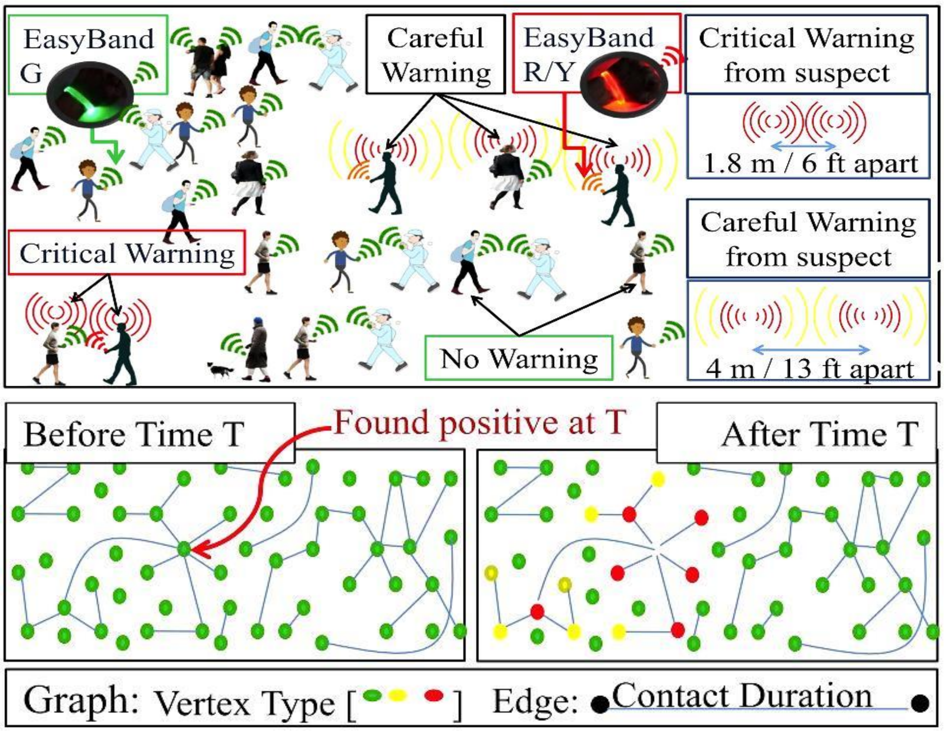


Figure 28. Contact graph obtained by *EasyBand* system before and after time T from a positive detection (Tripathy *et al.*, 2020).

One of these tracking systems is shown in ref. (Jeong *et al.*, 2019), whose operative principle is depicted in Figure 29. Specifically, a magnetometer-based method for contact tracing is proposed, which exploits linear correlations of smartphones and magnetometer readings to estimate the distance between phones and detect close contact events between individuals.

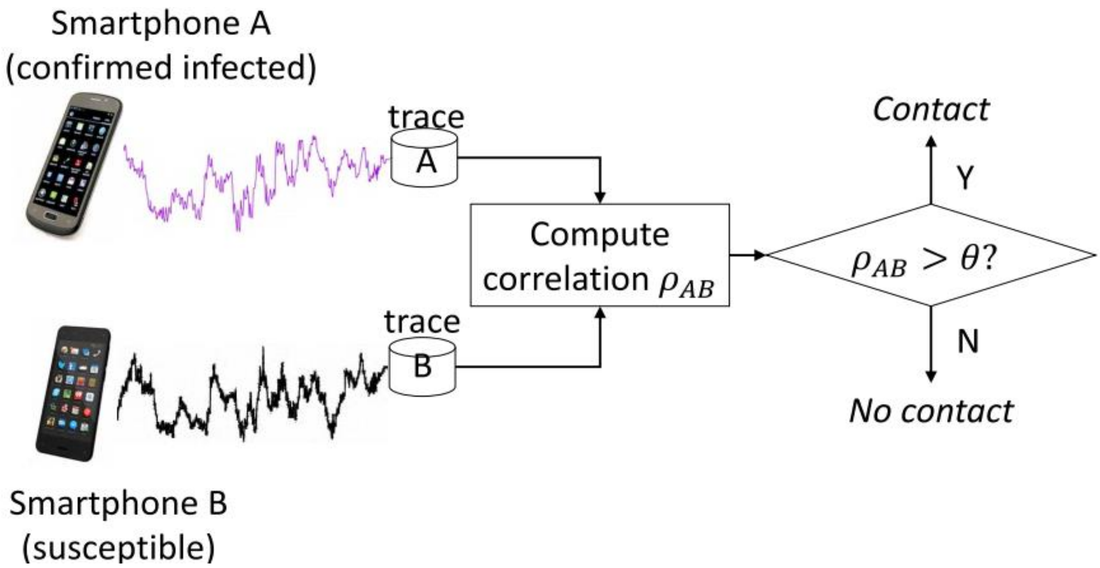


Figure 29. Smartphone magnetometer-based method for contact tracing and social distancing proposed in (Jeong *et al.*, 2019) (Jeong *et al.*, 2019).

To detect proximity are also widely used RF-based signals, such as Bluetooth (Liu *et al.*, 2014), WiFi (Sapiezynski *et al.*, 2016), and RFID-radio frequency identification (Bolic et al., 2015). Liu *et al.* (Liu *et al.*, 2014) built a model based on Bluetooth signal propagation for calculating distance values starting from Bluetooth received signal strength values. This model enables a precise distance resolution of 1 meter. Using WiFi and BLE, Sapiezynski *et al.* proposed a robust and accurate system capable of estimating the distance between individuals with a more precise distance resolution of 0.5 meters (Liu *et al.*, 2014). Bolic *et al.* use the backscatter signals from RFID tags to derive proximity with a small error of 0.3 meters (Bolic *et al.*, 2015).

Moreover, Farrahi *et al.* (Farrahi *et al.*, 2014) derive the cellular communication traces from information provided by online social networks, representing excellent indicators for contact tracing. In (Gupta *et al.*, 2020), Gupta *et al.* imagine the smart city and smart transportation system to ensure social distance. In the ref. (Polenta *et al.*, 2020), the authors employed the WiFi and Bluetooth signals from IoT devices to determine if two individuals respect social distances and developed a web app for users to manage the collected data.

Another interesting research can be found in (Tedeschi *et al.*, 2020), who proposed an IoT-based distance estimation scheme (using BLE) for tracing COVID-19 contacts, called IoTrace. IoTrace adopts a decentralized model, which addresses the privacy disclosure issues of the user device's location and overload.

RFID technology can also represent a good solution for implementing tracing and tracking systems to contain the COVID-19 spreading. S. Rajasekar *et al.*introduced a Tracking and Tracing solution based on an IoT framework for detecting and identifying social contacts using RFID technology and a portable wearable reader (Rajasekar, 2021). The authors consider the NFC protocol equipping the mobile phone as a reader. The mobile app detects if and when another tagged user is close to another one, recording and collecting information, passed to an edge device for the following processing. Once a suspected case is identified, the people who have been intercepted by the reader are alerted, through the mobile app, of the possible contagion, indicating him to make a quarantine. L. Garg *et al.* developed a new IoT model, based on RFID technology, for infection control and tracing of COVID-19 disease and preserving users' anonymity (Garg *et al.*, 2020a) (Figure 30). The model relies on the decentralization of the blockchain to detect and retrieve the chain data. It uses the blockchain to store the data ensuring anonymity using distributed ownership and control the stored data, processed to alert the users entered in contact with confirmed infected cases. A mobile application supports the proposed model, generating and storing the encryption key.

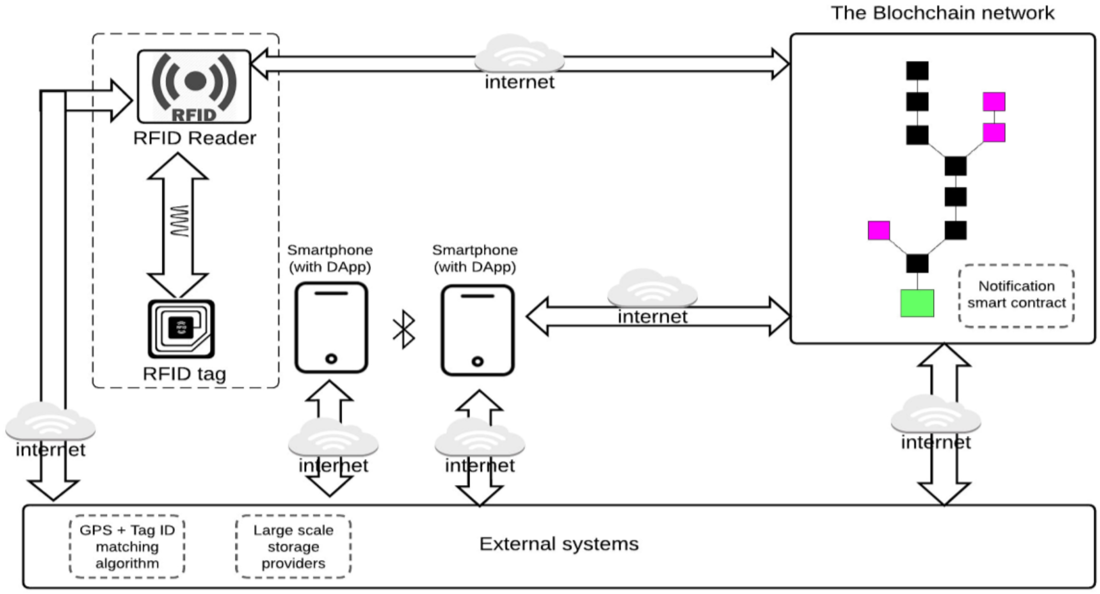


Figure 30. Blockchain diagram for anonymity preserving IoT-based contact tracing system based on RFID technology (Garg *et al.*, 2020).

5. Performance Comparison and critical analysis between discussed technologies, devices, and architectures

In this section, we report comparative analyses concerning the different technologies, sensing devices, and IoT frameworks discussed in the previous sections for early detecting patients affected by COVID-19 virus, avoiding the contagion spreading, helping the persons to comply the social distance, and tracing contacts of infected tested users, highlighting for each category, advantages, limitations and future potentialities.

In section 2, we have analyzed several wearable devices that track the patients' health conditions, identifying the first symptoms related to the COVID-19 infections, thus suggesting to the user further control to check the actual contagion. Finally, Table 2 reports a comparison of multi-parametric sensing devices, already discussed in section 2, from the point of view of detected parameters, application position, support of a cloud platform, detection technologies, and invasiveness to infer the most promising tools to face future pandemics.

As can be noted, the smart plaster reported in (Jeong et al. 2020), developed by researchers at Northwestern University and Chicago's Shirley Ryan AbilityLab, is featured by lightweight, small and low invasiveness, allowing continuous monitoring of patient's parameters, the remote definition of therapy, thus avoiding to increase the pressure on the health systems. Also, the Oura ring is a practical and ergonomic solution for detecting the user's principal vital signs, significant for diagnosing diseases with a heavy impact on cardio-respiratory apparatus, like pneumonia induced by COVID-19 virus, but, at the same time, maintaining very low invasiveness and high autonomy (Oura 2020). The VitalConnect patch is the most completed device in terms of the number of detected parameters, collecting data related to the conditions of the cardiovascular apparatus, posture, and activity level. However, the device aims to monitor patients' conditions inside a hospital, but it hardly can be applied in everyday life, given its dimensions (i.e. 10 cm x 3 cm) and reduced flexibility. We believe that these typology patch-type devices require efforts to reduce the sizes and the employment of flexible and biocompatible support materials.

Device	Detected Parameters	Application Position	Cloud Platform	Detection Technologies	Invasiveness
RespiraSense patch (PMD Solutions 2021)	RR	Chest	Yes	Piezoelectric	Medium
(Jeong *et al.*, 2020)	RR, HR, Body Temp.	Suprasternal notch	Yes	ECG, Accelerometry	Low
Lifesignals patch (Lifesignals 2020)	ECG, SpO_2, BP, RR, Skin Cond.	Chest	Yes	ECG, PPG, GSR, Accelerometry, Microphone	Low
Celsium thermometer (Celsium, 2020)	Body Temp.	Armpit	No	NTC thermistor	Medium
ECG Alert patch (ECG Alert 2020)	ECG, HR	Chest	Yes	ECG	Medium
Oura ring (Oura, 2020)	HR, SpO_2, HRV	Finger	Oura Cloud	PPG	Low
VitalConnect patch (VitalConnect, 2020)	Posture, RR, Body Temp ECG, fall detection, Activity level	Chest	Vista Solution™ Interface	ECG, PPG, GSR, Accelerometry	Medium
Lief Rx patch (Lief Therapeutics, 2019)	HRV	Chest	No	ECG	Medium

Table 2. Comparison between the multi-parameter sensing devices reported in section 2, in terms of detected parameters, application position, support of a cloud platform, detection technologies, and invasiveness

Furthermore, in subsection 2.1, we have reported an overview of the various models of innovative masks useful to limit the COVID-19 spreading and detect biophysical parameters (e.g., respiration rate) and adapt its operation as a function of them. The considered devices are fully reusable, employing a sterilizing mechanism (e.g., UV radiation, Joule effect), thus reducing the environmental impact related to their disposal, a critical issue that is emerging these days (Fadare and Okoffo, 2020). Table 3 reports a comparison of the different smarts masks previously discussed in subsection 2.1 regarding filtration efficiency, detected parameters, availability of self-sterilization and forced ventilation systems, and wearability.

Device	Filtration Efficiency	Detected Parameters	Sterilization mechanism	Forced Ventilation	Wearability
Active+ Halo (AirPoP Co. 2020)	99.3% (PFE) 99.9% (BFE)	RR, AQI	Washable	No	High
PuriCare Wearable Air (LG Group 2020)	93.5% (BFE) 97.3% (virus) 99.1% (pollen)	RR	UV radiation	Yes	Low
Project Hazel (Razer 2020)	95% (BFE)	-	UV radiation	Yes	Medium
Xiaomi Purely Mask (Xiaomi 2020)	95% (BFE)	RR, AQI, Acceleration	Disponsable filter	Yes	High
G-Volt mask (Dezeen 2019)	99% (BFE)	-	Joule-heating	No	High

Table 3. Comparison between the innovative masks discussed in subsection 2.1 regarding filtration efficiency, detected parameters, self-sterilization mechanism, presence of a ventilation system, and wearability.

In our opinion, the G-Volt mask is the best solution for fighting the future pandemics given its high filtration efficiency (i.e., 99%), good wearability, and mainly the self-sterilization capability implemented by a graphene-based filter, exploiting the local Joule-heating due to a small current flowing inside it (Dezeen, 2019). Also, the PuriCare Wearable Air mask (LG Group, 2020), despite its advanced functionalities (i.e. the sensing capability and availability of forced ventilation system), is featured by reduced wearability due to its non-negligible weight (i.e., 126 g).

In section 3, we have highlighted the importance of complying with the social distance rules as a tool to break the chain of contagion, thus containing the pandemic spreading; we have explored several commercial solutions to warn the user to the presence, at close distance, of another one. Different technologies have been used to implement such devices, like Bluetooth, BLE, LoraWAN, RFID, etc., affecting their performances in detecting capability and reliability. Table 4 summarises the devices discussed in section 3, comparing them from the point of view of detection technology, collected parameters, biofeedback typologies, wearability and cost.

As can be noticed, the considered solutions are very cheap, allowing the companies simple implementation of a monitoring system for keeping social distance in the workplaces and, thus, enabling a safe reopening of economic activities for the future financial restart. From the practical point of view, the badge-type devices, like Smart Badge™ (Abeeway, 2019), are featured by lower wearability compared to the wristband ones, such as the Close-To-Me (Close-To-Me, 2020), particularly important in the workplace, where the hand-free solutions are the main prerogative. Besides, the sensors' integration can allow a dual function, on the one hand, complying with distancing rules and monitoring the worker's conditions, enabling a detailed and accurate checking of pandemic spreading.

Device	Detection technology	Detected parameters	Biofeedback	Wearability	Cost
Close-to-me (Close-To-Me, 2020)	BLE	-	Visual Vibration	High	Low (64 €)
Safe Spacer ™ (Safe Spacer ™, 2020)	UWB (ultra-wideband)	-	Visual Acoustic Vibration	High	Low (100 €)
Smart Badge™ (Abeeway 2019)	BLE beacon Low GPS WiFi LoraWAN	-	Acoustic	Low	Low (100 €)
CrowdRanger (Crowdsaver 2020)	UWB	-	Visual Acoustic Vibration	Low	Low (89 €)
Nymi Workplace Wearables™ (Nymi Inc. 2021)	NFC BLE	HR, ECG, Accelerometer, Gyroscope, Fingerprint	Visual	High	Medium (200 €)

Table 4. Comparison between different wearable devices for keeping the social distance, discussed in the previous section 3, in terms of detection technology, detected parameters, biofeedback typology, wearability and cost.

Afterwards, we have discussed IoT-based frameworks for contact tracking and tracing application, combining wearable technologies, mobile applications and cloud computing, suitably developed to mitigate the impact of the COVID-19 pandemic, acting quickly on local outbreaks. Various technologies have been adopted, such as Bluetooth Low Energy (BLE), WiFi and RFID, for implementing these systems, often jointly employed to improve reliability and accuracy depending on the application scenario. Table 5 reports a comparison of the IoT-based tracking systems previously discussed in section 5 in term of detection technology, detected parameters, scalability and availability of supporting wearable devices, highlighting advantages, limitations, and future potentialities to identify the tools to fight the future pandemics. The scalability must be intended as systems capability to be applied to a broad audience of people, limiting the invasiveness on users' lives and ensuring their data security.

The Bluetooth beacons, WiFi networks, and cellular signals are widely analysed to extract information about several human behaviours, including social interactions. In addition, Bluetooth offers several advantages, such as small device's dimensions, low cost and power consumption, and broad compatibility with smart devices.

Work	Detection Technology	Detected parameters	Scalability	Availability of supporting wearable device
Immuni app (Immuni, 2020)	BLE	Distance Time duration	Medium	No
TraceTogether (TraceTogether Tokens 2020)	BLE	Distance Contact time duration	Medium	Yes
GoCoronaGo (Simmhan *et al.*, 2020)	BLE	Distance Contact time duration	Medium	No
(Girolami *et al.*, 2020)	BLE	Distance Contact time duration	Medium	Yes
EasyBand (Tripathy *et al.*, 2020	BLE	Distance Contact time duration	Medium	Yes
(Paek *et al.*, 2010)	GPS	Distance	Low	No
(Jeong *et al.*, 2019)	Magneto-meter-based	Magnetic field Contact time duration	Low	No
(Polenta *et al.*, 2020)	BLE	Distance	Medium	Yes
(Garg et al., 2020)	RFID, NFC	Distance	Low	Yes
(Rajasekar, 2021)	RFID, NFC	Tag Detection	Low	Yes
(Sapiezynski *et al.*, 2016)	WiFi	Distance Contact time duration	High	No

Table 5. Comparison between different IoT-based frameworks for contact tracking and tracing application reported in the scientific literature, in terms of detection technology, detected parameters, scalability and availability of supporting wearable devices.

However, Bluetooth solutions are featured by limited scalability due to their limited interoperability with the manual tracking systems, related to the collaboration with health systems, low download rates, and distrust linked to security and privacy reasons. Alternatively to the BLE tracking, frameworks for collecting and analysing GPS and WiFi localization data are widely investigated by telecommunication companies and government authorities to detect social contacts. WiFi positioning systems can accurately determine the distance between two individuals from the set of listened access points, obtaining a reliable and scalable, without needing additional hardware components. This approach requires WiFi coverage, however now widespread both in indoor and outdoor environments. The telecommunication operators can also exploit the cellular signal to determine a mobile phone's position. Triangulating the information from the home location registers (HLRs) of different mobile stations, the user's location can be established with great precision. We believe that this approach is the best solution to determine information on large-scale population behaviours without any hardware modifications, processing the data already available in the communication infrastructure, capturing in quasi-real-time mobility information of a significant number of people.

The fundamental aspect related to the collection of social interaction data is the privacy implication. Different strategies are available for managing the data collection: centralized, semi-centralized, and decentralized. In the first one, the user periodically sends the Bluetooth device IDs to a backend service; in the semi-decentralized approach, the relation between the app and the device ID is remotely stored, whereas the contact information is collected on the local device (BlueTrace 2020). In contrast, in a decentralized solution, the Bluetooth device IDs related to the social contacts are stored in the local devices, sending them only when the user tests positive. The contact data should be collected into a remote central database in an encrypted manner for protecting it from dumping and data branches. For instance, the *GoCoronaGo* system uses a centralized approach based on *Unique ID* and *Device ID* assigned by the central server during the installation phase to keep user anonymity (Simmhan *et al.*, 2020). TraceTogether app employs IDs assigned by the central server or locally generated during the contact tracing activity (TraceTogether Tokens, 2020). Thus, the system doesn't need any personal data related to the user, recognized only by a random ID periodically changed. In contrast, the Immuni app paradigm recently switched from a centralized to a decentralized approach to enhance privacy protection. Particularly, the user smartphone locally collects the random IDs of close people, produced according to a key stored in the device during the installation process. If the user contracts the virus, an unlock code is provided to transfer the acquired IDs to the central server (Immuni,2020). The semi-centralized approach is used by BlueTrace and Aarogya Setu (Aarogya Setu, 2020) applications developed by the Australian and Indian governments to face the COVID-19 pandemic.

Usually, the tracing apps are supported by geolocalization data provided by a GPS receiver, stored inside a local SQLite database on the smartphone, making them periodically available to the central server.

In (Kuhn *et al.*, 2021), the authors explored the numerous protocols proposed by the scientific community for guaranteeing the privacy and anonymity of collected tracking information according to the data protection rules; the analysed protocols concern both the centralized and decentralized approaches (such as decentralized privacy-preserving proximity tracing DP3T (DP3T, 2021), Google-Apple exposure notification framework GAEN (Apple Inc., 2021), pan-European privacy-preserving proximity tracing PEPPT-PT (PEPP-PT, 2020), ROBERT- ROBust and Privacy-PresERving Proximity Tracing protocols (PRIVATICS team Inria and Fraunhofer AISEC 2021), etc.). Furthermore, the authors proposed a critical analysis of the considered approaches to highlight their strengths and weaknesses. Finally, the reported discussion indicated none of the discussed protocols could ensure localization and identity protection from users and server points of view. In particular, a centralized approach could expose the localization data of alerted users, as well as for the hybrid solutions, such as DESIRE (Castelluccia *et al.*, 2020) and ConTraCorona protocols (Beskorovajnov *et al.*, 2020).

In this context, R. Sun *et al.* developed a security and privacy detection method, called *Covid Guardian*, which identifies the shortcomings of the protection systems by combining three steps: PII (personal identification information) analysis, dataflow analysis to detect privacy hazards, and malware detection (Sun *et al.*, 2020). Using this developed assessment method, the authors tested 40 apps, including TraceToghether, COVIDSafe (Health, 2020), Aarogya Setu, etc.; the obtained results demonstrated that no application could completely safeguard users' security and privacy from all threads.

6. Conclusions

The COVID-19 pandemic, afflicting the world population, is pushing the companies and scientific community to develop solutions to contain the virus's spread, early detect the first symptoms of the infection, and monitor the health conditions of infected patients during the quarantine. This manuscript has provided a careful and in-depth analysis of the IoT-based wearable devices for remotely monitoring the biophysical parameters correlated to the COVID-19 disease, thus avoiding crowding the hospitals. We have also explored several commercial wearable solutions to make users aware of social distancing in workplaces, fundamental for reopening economic activities heavily affected by long periods of lockdown. Besides, an overview of the innovative architectures based on IoT, wearable devices, and cloud computing has been reported to track the contacts of tested infected individuals, breaking down the contagion chain. Finally, we've critically analyzed and compared the different discussed solutions, opening ideas for investigation and highlighting potentialities for developing innovative tools for facing future pandemics.

Our scientific work focuses on applications based on wearable devices for fighting against the COVID-19 pandemic, including the extremely popular traceing mobile applications, unlike similar review papers that range over other monitoring solutions (drones, robotic applications, etc.) (Nasajpour et al. 2020; Al-Humairi and Kamal 2021). Furthermore, review papers covering the same topics do not always consider commercial devices, including intelligent masks, extensively investigated in the proposed research work (Chamola *et al.*, 2020; Suresh Kumar *et al.*, 2021). Besides, in our review paper, we dedicated a entire section to wearable commercial solutions (e.g. smart badge, smartwatches, smart bracelets, etc.) for complying with the social distancing rules, mainly in workplaces, which are allowing a rapid and safe resumption of economic activities; similar works rarely consider this topic (Yousif *et al.*, 2021). Finally, we also explored several wearable and implantable applications for monitoring the effects of COVID-19 disease on the cardiovascular system, usually not covered by similar works (Hedayatipour and Mcfarlane 2020;

Behar *et al.*, 2020). Therefore, we believe that the accuracy and completeness of the proposed scientific work represent its actual added value, providing the reader with a comprehensive overview of the IoT-based solutions to tackle the COVID-19 pandemic.

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