Microwaves in supporting global challenges

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***Abstract* — This essay explores how microwave technologies, particularly integrated microwave, millimetre-wave or even terahertz circuits, could support solving global challenges. Section I serves as a short introduction of the topic, while some particular challenges are described and possible solutions are further explained in sections II to VII. This is done by mentioning already existing solutions as well as current and future research topics. At last, section VIII gives a conclusion on the topic and highlights some of the key aspects.**

***Keywords* — Microwaves, IoT, 6G, Microwave ICs**

I. Introduction

The study of microwaves and high frequency electronics as well as the underlying physics and material sciences lead to great advances over the last decades and culminated in many key technologies of modern societies. The application spectrum started from military devices like radar and then went into further use in communications technologies. Nowadays, microwave technologies and integrated microwave circuits have penetrated almost every part of our daily lives and are becoming more and more relevant in industry, medicine and transportation. With such a huge diversity of desired products come very different requirements regarding parameters like power levels, energy efficiency and tolerance to environmental conditions. Therefore many different materials were developed and are still under research, with Silicon being the most widespread. However, there are other semiconductor compounds like for example Indium-Phosphide or Gallium-Arsenide, which are still under active research but show promising potential for future use.

Regarding the impact of microwave technologies, it is obvious that they will also be a key component to tackle the challenges and problems of the future. Mankind faces many obstacles ranging from climate change, resource management and scarcity, population growth, economical and social development and the associated increased demand for certain goods and services as well as problems like aging societies, where the need , for example, sophisticated medical care is opposing a shrinking number of medical personnel. Besides all these challenges, societies still want to raise their standard of living, which is also associated with drawbacks like increased resource use and carbon footprint. Also, a more widespread use of technology and higher standard of living leads to increased energy consumption, so improved energy efficiency is a common goal. Overall, humanity is at a point where we need to decouple increasing our own prosperity from damaging and threatening the planet and ecosystems around us. While microwave technologies certainly won't solve this problem on their own, they can still be a viable part of the solution.

II. Climate Change and Pollution

As well known, climate change is one of the most pressing global issues of our time. If humanity isn't reducing its carbon emissions, there's the potential for dramatic changes, which will significantly impact our current way of living and will force widespread and profound adaptions. 196 nations agreed on keeping the man-made temperature increase well below $2°C$ by signing the Paris Agreement. To achieve this, there are some major transformations that need to be performed, like for example the change from fossil-based fuels to renewable energy for electricity as well as other areas like transportation and heating. This requires a complete overhaul of our current electricity grids, leading to so called Smart Grids. These enable integration of fluctuating power generation, like wind and solar power, together with energy storage technologies, like batteries, hydrogen or electric vehicles (EVs), and the possibility to better manage load conditions of the grid. Microwave integrated circuits will play a role in the required data acquisition and communications infrastructure needed. A huge number of sensors will gather data, which is processed by a central processing unit, to then derive controls for the whole grid. This enables better load conditions and stability of the grid as well as increased efficiency in energy distribution by coordinating the different participants. A proper implementation of these ideas would require a huge number of sensors, with total numbers being in the order of several million pieces. Therefore, this presents a big opportunity for new integrated circuits. However, a concrete fundamental structure still needs to be derived, but many governments are working on respective plans[1][2].

As mentioned before, electric vehicles will also be an important part of changing towards a carbon-neutral way of living. Cars themselves already are a prime use-case for microwave technologies, e.g., in automotive radar systems. Hence, there already is a large market for microwave technologies, which is expected to grow even further with autonomous driving. Microwave ICs will also be important for Smart Transportation systems. As before, these systems rely on a large number of deployed sensors gathering traffic data. By using sophisticated models, this data allows for a more efficient way of directing traffic in cities and whole regions. This leads to more efficient resource use, while simultaneously reducing time spent in traffic and saving lives.

Another possible application is the development of smart road infrastructure, which allows for communication between cars and traffic surroundings. All of these uses need a large number of ICs and thus present big economical potential in the future, but are currently still in development[3][4][5][6]. Another challenge for humanity is increasing environmental pollution. On one side, there is direct pollution caused by waste being thrown away into nature, and on the other hand, there is a more indirect pollution of natural resources like water. This problem could be tackled by using Smart Waste and Water Management systems. They offer increased efficiency of for example garbage collection, to reduce the amount of waste, that isn't handled properly, and also enable monitoring of certain parameters of ecosystems to avoid damage to them and increase air and water quality. Right now, such management systems are topic of research activities, but they offer great potential for microwave ICs[3][4][5][6].

III. Natural Disasters

Natural disasters, like floods, storms and other extreme weather conditions, are in many ways connected to climate change, because their probability and severity is increasing with rising global temperatures. This also leads to more damages to urban infrastructure like buildings, which could then collapse and trap people. Another possible cause for this are earthquakes. Their exact occurrence is quite unpredictable and some big earthquakes are expected to happen somewhere in the near future. Microwave technologies can be used in the aftermath of such events, when search and rescue operations need to be performed. They can offer assistance when localizing victims under debris to reduce rescuing times allowing for faster medical treatment. The localization is done by using the smartphones of buried victims. One approach is to scan the disaster site with an antenna array and search for a maximum in the magnitude of the received signal. Another possibility is the setup of a mobile communications base station, which is then used to jam all other base stations in the area and send out a signal to nearby phones forcing them to send out a signal with maximum power. These signals could then be located by using handheld devices. While research and field studies show good performance, these systems would need to be very robust to comply with environmental conditions present at disaster sites. Also, there isn't a huge market for these technologies, since only a few organizations would have a need for this equipment. Hence, these devices would probably stay expensive and only be produced in very small quantities. A more widespread use and reduced manufacturing costs of microwave technologies could possibly bring down prices and support this kind of application[7][8].

IV. Energy Efficiency

Another global challenge is better energy efficiency. Because of the increasing number of electronic devices, which is expected to keep growing, more and more energy is used. The only way to reduce the energy consumption and the associated carbon footprint is to increase efficiency. Microwave technologies and ICs have the potential to increased efficiency and providing the desired performance by employing new materials and more sophisticated circuits. Gallium-Nitride based power electronics, for example, offer a lower parasitic resistance and better power handling capabilities than current technologies, while higher switching frequencies could be used to reduce losses even more. They could be used to replace current power amplifiers in mobile communications base stations, which offers a good market perspective for medium volumes. Increased efficiency in integrated circuits will also be greatly beneficial, especially when going to higher frequencies. Since ICs are mass produced, the volumes would be quite high, while individual cost are low, hence the development needs to be quite cheap. Lack of mass production is one of the biggest drawbacks of the previously mentioned technologies, therefore the technology readiness level (TRL) and yield need to be improved, to aid in global circular economies. An important step to increase the TRL is accurate device modeling to ensure good simulation results. These models are then used for a process design kit, which allows for the design and fabrication of microwave ICs[9].

Communication technologies are another area, where energy efficiency is of great importance, especially considering mobile applications. As more and more people are getting access to these technologies, the number of devices and infrastructure grows, hence increasing power consumption. The introduction of new and better microwave ICs could play a key role for increasing efficiency in communications. These ICs are used inside the small personal devices, like smartphones and computer, as well as in base stations and telecommunications towers, for example as a power amplifier. Thus there are different market sizes and impacts to be expected. The market for personal devices is huge with millions of units, while infrastructure only needs small to medium quantities. Hence a small improvement in efficiency for personal devices still has a big impact because of the huge volumes. Also, with new communications standards, like 6G, there is the need for new types of microwave circuits and technologies. Envisioned peak data rates of 1 TBps with user data rates of 1 GBps, while also maintaining low latencies of below 0.1 ms, are some of the key performance indicators. Other goals like reliability, location estimation and expansion to non-terrestrial areas pose new, previously unmatched problems for the design and application of integrated circuits. Evolving from 5G, the 6G communication will consist of a growing number of object oriented communications. This evolution can also be seen, when taking a look at the different performance aspects intrinsic to 6G, which are Hyper-bandwidth, Hyper-trust and Hyper-connection as well as Hyper-precision, -performance and -intelligence. These six goals ought to be achieved by means of (sub-)THz communications,medium access control (MAC) and radio resource management (RRM), new physical-layer techniques, AI-based communication systems, AI-native networks, localization and sensing as well as non-terrestrial networks. Microwave integrated circuits will play an important role in almost all of these fields. For example, (sub-)THz (0.1-10 THz) systems are basically just an extension of microwave communication systems to higher frequencies. Right now, integrated circuits for these frequencies are still under heavy research, but are slowly getting more available. Their efficiency, however, is quite bad at the moment, but it is increasing steadily with the use of new and improved technologies. For example, D-Band (130-174 GHz) is envisioned to be used for communications over ranges over 10m. There are already some demonstrator systems showing promising results with ongoing research and also some major companies like Samsung, Nokia, LG and Ericsson committed in developing communication systems for that frequency range. On another note, THz frequencies allow for ultra-wide bandwidths of 10 GHz and more. These frequencies are exemplary for the microwave range, allowing microwave integrated circuits to play an important role in baseband signal processing. Hence the development of 6G will have an impact several frequency ranges, like up to 10 GHz for baseband processing, 20-60 GHz with reuse of 5G technology and 100 GHz and beyond[10].

As mentioned before, Internet of Things (IoT) and distributed sensor networks are two more use cases, that benefit greatly from increased efficiency. There is an ongoing development to connect application areas that until recently were completely separated from communications technologies. Many of these applications include the integration of sensors and data transmission, thus requiring new and innovative ways to combine different functions into one integrated circuit. In general, Internet of Things allows connecting many different devices from very different domains. Examples includes household appliances, like washing machines or kitchen devices and extend into areas like environmental sensing and Industry 4.0 /5.0. Energy efficiency is an important metric for these devices and also important for consumers[11].

Similarly, Industry 4.0/5.0 relies on the integration of a huge number of different sensors, connecting areas like manufacturing, quality control and logistics to derive controlling decisions. Here, the requirements about reliability are very strict, considering that mistakes could lead to huge economical damage or even accidents between human workers and robots. Therefore, there is a need for high precision data and localization as well as signal processing, which can all be offered by using microwave integrated circuits. These high performance ICs typically need quite a lot of power, so better efficiency is desired. A proper implementation of these sensor networks would increase efficiency of industrial processes and better coordinate workflows, while reducing stress on workers and raising prosperity. However, there are still challenges, like standardization and security aspects, associated with this topic, but these are part of current research and also first proposal for solutions have been made[12].

V. Population Growth and Hunger

Feeding a growing number of people, fighting hunger in poor regions and securing food supply with increasing effects of climate change are major challenges of the future. These are even more severe for less developed countries, since they don't have the necessary financial means. The use of sensor networks and microwave technology could greatly increase productiveness and efficiency of farms by aiding in monitoring of crops and soil conditions. These networks rely on wireless probes for measuring different parameters of soil or crops, that transmit their data to a central computing station, where data is processed. Technology for this application needs a high tolerance to different environmental factors like heat and humidity and should consume as little energy as possible to keep maintenance low. By proper implementation, this could offer a new way to increase yield and reduce workload for farmers, since remote monitoring and intelligent data management would be possible. It would also allow for fast intervention, when weather conditions are changing and more efficient usage of water and fertilizer, leading to a reduction in resource usage and lesser effects on the environment. Also, food waste could be reduced since farmers could gain access to market information. The increase in efficiency would help tackling challenges like extended land use, soil depletion and climate change, which are impacting humanity on a global scale. However, there are still great obstacles ahead, like a holistic system architecture, that focuses on the whole life-cycle of crops. Another problem is the price, which could lead to bigger barriers for small- and middle-scale farmers, especially in poor countries. Furthermore, this technology requires an easy-to-use interface, to not overwhelm farmers with complexity[13].

VI. Social Problems and Healthcare

Besides natural and resource problems, there are also social problems concerning the communal living of humans as well as problems like aging societies, which lead to other issues like increased healthcare needs. Microwave integrated circuits can also help tackling these challenges. In the bigger picture, IoT technologies can be deployed in large-scale sensor networks in cities to gather data for different areas. These include water and waste management and transportation, as mentioned previously, but also energy and social cohesion. Of course, these are general problems and every city has their own subset of specifics regarding these topics, which require a unique approach considering the respective boundary conditions. However, Smart Cities allow for a unique interaction between official institutions and the local communities guided by the cities infrastructure. To get a better overview, there is a comprehensive categorization into six smart city domains. These are Natural Resources and Energy, Transportation and Mobility, Built Infrastructure, Industry and Human Resources, Governance and Living.

Taking a look at these topics, it is noticeable that many of these are related to previously presented topics. This shows the strong interconnection between different smart technologies and how broad the spectrum of IoT really is. But there are also new topics here, like public lighting and other fundamental services, which need to be provided by the city. As for previous IoT applications, there is a huge market associated with Smart Cities, however, concrete implementations are just in a research state.

The domain of Living focuses more on the social side of problems, including topics like public spaces and public safety. This would require the processing of data generated by user devices to, for example, provide local information about arts, cultural institutions and services to visitors and tourists. Microwave integrated circuits would play an important role by being part of already existing mobile devices like phones, which could send for example location-based data. Prediction of social events and problems could prove difficult, due to the complicated nature of peoples behaviour and would require trained networks, which are based on previous happenings in the same city.

Intelligent road infrastructure could be used to assist Smart Transportation systems in the future. The overall goal of more energy efficiency and less pollution is achieved by communicating with road infrastructure, where the data can then be used for traffic control. Many solutions are focusing on building Internet-based Ad-Hoc-Networks for this purpose. However, while promising great potential, these networks still need much development and testing before they can be deployed on large scales. But seeing the current interest in IoT and AI-computing, this only seems like a matter of time[3][4][5][6].

Another important application, especially when considering the growing number of old people and the decrease in well-trained personnel, is medicine. Current systems often rely on trained operators to achieve good diagnoses. Microwave systems have the potential to reduce the work load of these operators, thus increasing the quality of offered medical services even in rural areas. For example, a THz-spectroscopy system based on a W-Band signal (75-111 GHz) used for blood coagulation measurement is presented in [14]. The evaluation of blood coagulation is vital for people with venous thrombosis, pulmonary embolism and other cardiovascular diseases to avoid haemorrhage or thromboembolism. The proposed system offers the advantage of not needing any consumables or reagents to stimulate blood coagulation and thus could possibly be used for portable systems and generally easier application of blood coagulation measurements. It has the basic structure of a wireless transceiver system, consisting of a frequency synthesizer with respective multipliers, which sends out a signal through a WR-10 waveguide, which is placed over a blood droplet. The reflected signal is then downconverted by a mixer and its amplitude and phase are recorded and changes over time are evaluated. Changes in the reflectivity can be observed until up to 10 minutes after the first exposure but the meaning of these changes, however, still needs to be further investigated to accurately make conclusions and to deembed the unwanted effects like the drying of the sample [14].

A quite similar system for scanning of the cornea is described in [15], where the operating frequency is 650 GHz. Again, a measurement of the dielectric properties is performed to characterize the cornea. While the system itself is quite bulky, it offers non-contact cornea measurement, which can't be done with current technology. In this paper, the operation is functionally demonstrated, but there are still some unsolved issues like eye movements and tear film inconsistencies[15].

Also, radar systems can be used for monitoring the vital parameters of patients without attaching any cables or probes to their bodies. This technique is also easily applicable to infants, which would otherwise need special electrode sets, or burn victims, where you can't attach the electrodes to burnt areas. Microwave radars offer the advantage of not putting any constraints on the patients mobility and allow for long-term monitoring of vital signs, even when the patient is sleeping. So overall, radar-based vital parameter detection promises simpler and higher quality monitoring, while simultaneously reducing the workload on caretakers. These systems could also be used in home applications to detect potential emergencies and thus could improve health care in remote locations and rural areas. The basic structure is quite simple and only consists of a radar connected to a computer or digital signal processor for signal analysis. The subject is located inside the radars antenna view. The radiated radar signal then gets reflected by the patients body and its amplitude and most importantly phase are evaluated after receiving. By monitoring the phase difference over time, it is possible to determine the distance change, which can them be filtered to extract heartbeat and breathing signals.

In a typical experimental setup, the only cables attached to the patient belong to the reference sensor. Also, the scenario can be easily extended to patients laying inside a hospital bed with the radar being mounted at the ceiling or inside the bed frame under the patient. While these systems are still in development, there are many research groups pushing towards making a usable product, with some of them already doing clinical studies[16][17].

Other applications also include cancer monitoring, which could be vital seeing the growing number of cancer patients. The measurement also relies on capturing the dielectric properties of the body tissue, however, it is quite complicated because the tissue is heterogeneous and the permittivity is unknown. Hence the actual permittivity is extracted during the measurement to improve the imaging quality. This approach allows for 3D-mapping, as well as long term monitoring, since the transmitted power is very small and the used microwave frequencies are non-ionizing. This application offers supplementary capabilities to normal X-ray imaging methods, which improves the quality of the cancer treatment[18].

In general however, healthcare technologies need extensive testing, robust systems and compliance with strict regulations to be used on patients in real situations. Also market size is quite small, which makes systems more expensive. This obviously presents a big obstacle for microwave technologies since reliable wire-bound solutions are readily available, quite cheap and the standard option. But many publications demonstrate the feasibility and accuracy of microwave systems, so more research and widespread testing could lead to ready-to-use implementations [14][15][17][16][18].

VII. Future Research

Another use for microwave technologies is future research. New electronics can help in going beyond the current boundaries of measurement and experimental setups, offering new ways of investigating things. Also, they can offer new ways of getting data. An example is the project mentioned in [19], where a tracking sensor for bats was successfully developed and tested. The main focus for the development was a compact and low-power realization of the sensor, that allows for mounting on the back of the bats and long monitoring times. The tests relied on a combination of sensors together with a base station network and showed great results for further experiments. Performance requirements were strict, since bats move quickly and can cover huge areas, while also interacting with other bats. The location as well as encounter information was of interest for the scientist and needed to be captured in a good resolution. One of the mentioned bottlenecks was communication data rate, which limited the amount of data send towards the base stations. Microwave integrated circuits could be used to increase the data rate and for faster capture and transmission of information[19][20][21].

On another note, new sensors would enable research in places which are not suitable for humans like the deep sea or volcanic areas. Distributed sensor networks could be used in these harsh conditions to monitor certain chemicals or other parameters, to for example gain information about changes quickly[20][21].

Another area of interest are space technologies. As seen in recent years, microwave technologies can improve the capability of satellites or other space vehicles to perform measuring and remote sensing tasks of atmospheric or environmental quantities, which would help our understanding of the ecosystem of the earth or the monitoring of carbon dioxide levels, as an example. This has been done for the earths atmosphere as well as for the atmosphere of other planets and thus presents a valuable opportunity to gain information about objects in the solar system. The retrieved information allows to determine the abundance and spatial distribution of microwave absorbing substances inside the planetary atmosphere[22].

With an increasing number of space vehicles like satellites and rockets as well as the efforts to enable space travelling, there is a growing number of debris surrounding the earth, which could possibly destroy stationary satellites. Employing radars is a way to detect the presence, position and movement of these objects and to derive proper maneuvering techniques to avoid collisions. There are already investigations of how to implement these technologies and put them to use. Microwave and mmWave radars employing multiple-in multiple-out (MIMO) architectures are promising candidates, which already show good results in terrestrial applications. Respective signal processing would allow for object identification as well as object tracking to then derive maneuvers to avoid a collision[23]. As mentioned before when talking about 6G communications, non-terrestrial networks should be developed in the future. On one hand, these require a communication link between the satellites and earth, and on the other hand, also communication between satellites. These are exemplary use cases for microwave technologies, since already existing satellite communications are performed using X-Band (8-12 GHz), K-Band (18-27 GHz) and V-Band (40-75 GHz). The growing demand in this area will enable many more applications for microwave integrated circuits. Currently however, there are no exact specifications of how to use which frequency, which would need to be standardized, to ensure proper communications. Generally, space technologies offer growing market opportunities with their respective new use cases[24].

VIII. Conclusion

In conclusion, the use of microwave technology has already made a deep impact on our everyday lives today and will continue to do so in the future. It is a key component to help overcoming the current and future problems of our society and mankind as a whole, like shifting towards a sustainable way of living, stopping climate change, providing food, connectivity and safety to a growing number of people and increasing efficiency. This should be achieved while simultaneously allowing for economic and social prosperity and improvements. Different global challenges and some respective solutions were discussed in this paper, while key points and remaining problems were highlighted. All of these applications are supported by research, which is relentlessly looking for ways of improving microwave technologies in the respective areas. For some of these use cases, there already are working systems, e.g., prototypes for radar-based vital sign detection, or an underlying structure, that can be used, like in the case of 6G, which uses the previous 5G standard and extends its functionalities. For these technologies, application-readiness is just a small step away. For others, like for example Smart Grids, Smart Cities and IoT in agriculture, it's still a long way until they can finally be fully utilized in real-world scenarios.

However, a widespread use of microwave, millimetre-wave and terahertz systems, especially combined with a focus on integrated circuits, combined with technologies like Internet of Things offers a completely new way of collecting and using data, connecting and improving different parts of our lives. To fulfill the predictions envisioned by the researchers a lot more work needs to be done and microwave technologies need to get to a higher level of technology readiness and ease of use. Another important factor is the price, which needs to go down to enable mass production and spark interest in industry and consumer applications. Considering the different market sizes and opportunities, prices will probably go down first in IoT and communications applications, while costs for medical devices probably will stay high, because of lower quantities. With more and more research being done and also new ways of getting knowledge and solving problems, there will be even further improvements about microwave technologies. So all together, there is a bright future ahead for microwave integrated circuits and they will be an integral part in fighting the big problems humanity is facing right now.

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