EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Brussels, 4 June 2019

COST 040/19

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Future communications with higher-symmetric engineered artificial materials" (SyMat) CA18223**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Future communications with higher-symmetric engineered artificial materials approved by the Committee of Senior Officials through written procedure on 4 June 2019.

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COST
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA18223
FUTURE COMMUNICATIONS WITH HIGHER-SYMMETRIC ENGINEERED ARTIFICIAL MATERIALS (SyMat)

The COST Member Countries and/or the COST Cooperating State, accepting the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action (the Action), referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any new document amending or replacing them:

a. "Rules for Participation in and Implementation of COST Activities" (COST 132/14 REV2);
b. "COST Action Proposal Submission, Evaluation, Selection and Approval" (COST 133/14 REV);
c. "COST Action Management, Monitoring and Final Assessment" (COST 134/14 REV2);
d. "COST International Cooperation and Specific Organisations Participation" (COST 135/14 REV).

The main aim and objective of the Action is to promote a research community proposing solutions for connections in today's society by investigating electromagnetic properties of artificial materials whose unit cells have higher symmetries. These special symmetries can lead to ultra large bandwidth of operation, reduced losses, enhanced stopbands for electromagnetic bandgaps, and protected propagation of confined waves. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 56 million in 2018.

The MoU will enter into force once at least seven (7) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14 REV2.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14 REV2.

OVERVIEW

Summary

The SyMat COST Action has the ambition to promote an international research community proposing innovative solutions to the demand of omnipresent connections in today's society. Higher data rates and shared platforms can only be achieved if a new class of communicating devices becomes available at millimeter waves.

SyMat will investigate the electromagnetic properties of new classes of metamaterials and metasurfaces. They are made of periodic cells invariant under higher symmetries, such as glide or twist symmetries. As an example, while a periodic structure is invariant under translations, a glide-symmetric structure is also invariant under a translation and a mirroring. These symmetries lead to marvelous uncommon properties: ultra large bandwidth of operation, reduced losses, scanning capabilities, and enhanced stopband for Electromagnetic Bandgap materials. They have the potential to meet the expectation of new communication devices.

The novelty of the subject motivates the need for a diverse network: different scientific backgrounds – scientists working in physics, engineering, numerical modelling, together with investigators working in companies - will contribute to meaningful research lines. Participation of young researchers and female investigators is especially expected. SyMat will contribute to the impact of European research on public scientific awareness, societal change and economic development, by granting the know-how of an emerging technology and enabling transfer of results for exploitation.

Areas of Expertise Relevant for the Action	Keywords
● Electrical engineering, electronic engineering, Information engineering: Communications engineering and systems (select for additional explanation) ● Electrical engineering, electronic engineering, Information engineering: Computational modelling and simulation ● Physical Sciences: Electromagnetism (theory) ● Physical Sciences: Optics, non-linear optics (theory) ● Physical Sciences: Nanophysics: nanoelectronics, nanophotonics, nanomagnetism or classify	● Antennas and propagation ● Communications ● Artificial materials ● Electromagnetic modelling ● Symmetries

Specific Objectives

To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

● Develop specific models of higher-symmetric materials to describe and design new prototypes materials, by bringing together scientists with complementary backgrounds (theoretical and applicative). Existing models cannot correctly characterize higher-symmetric materials due to strong interactions among scatterers, and new tools need to be developed for analysis and design.

● Designing new radiating systems by exploiting higher-symmetric geometries to achieve performance beyond the state-of-the-art in terms of beam-scanning capabilities, operational bandwidth, losses in different technologies such as SIW, gap waveguides, planar PCB, 3-D printable materials. Relevant specifications will be made available by interacting with the companies participating to the Action.

● Designing new guiding-wave devices by exploiting higher-symmetric geometries to achieve performance beyond the state-of-the-art in terms of insertion losses, bandwidth, isolation, losses in different technologies such as SIW, gap waveguides, planar PCB, 3-D printable materials. Relevant specifications will be made available by interacting with the companies participating to the Action.

● Reaching stakeholders to communicate on higher-symmetry materials. The topic is new and there is very limited information among stakeholders. The Action aims to make them understanding the potential of these kind of artificial materials for communications.

Capacity Building

● Avoid fragmentation of research and share negative results among different researchers so that efforts will be joined rather than competitive. The Action will avoid duplicating efforts on the same subjects and will prevent from time-consuming modifications of planned actions.

● Enable researchers to implement their results by accessing a shared network of infrastructures for fabrication/measurements. A list of available measurement/simulation facilities, together with details on their availability for activities of the Action (period of the year, technical staff availability, access procedures) will be on the Action website.

● Provide Early Career Investigators (ECI) with training in the framework of doctoral schools on state-of-the-art offered by academia and industry partners (currently non-existing on this subject) and short missions (measured by the number of ECI involved in STSM and management responsibilities).

● Promoting a balanced female/male environment. The ratio female/male will be increased when extending the Action to new participants in order to achieve a balanced environment. This balance will be kept in the scientific and dissemination activities to implicitly communicate on this subject (measured by the evolution of the ratio female/male).

● Extending the network beyond research-intensive countries. The extension of the Action will be performed with special care toward COST Near-Neighbour Countries (NNC) and Inclusiveness Target Countries (ITC) (measured by the number of ITC and NNC participants joining the Action).

TECHNICAL ANNEX

1 S&T EXCELLENCE

1.1 SOUNDNESS OF THE CHALLENGE

1.1.1 DESCRIPTION OF THE STATE-OF-THE-ART

In the approaching internet-of-things (IoT) revolution, higher data rates and shared platforms among different services and users are already stimulating **a revolution in terms of** data processing approaches and device technologies (e.g., the next generation 5G communication standards and satellite communications). The European “5G PPP” program (https://5g-ppp.eu/) will enable 1000 times higher wireless area capacity compared to 2010, and **the available bandwidth can only be found at millimetre waves** [1]. Meanwhile, satellite communications are also moving up in frequency into the Ka band (17.7–21.2 and 27.5–31 GHz for transmitter and receiver, respectively) where more bandwidth is available and terminal size can be reduced [2]. These new global trends are pivotal for the connectivity of our modern society. Work productivity heavily depends on the quality of information exchange and network connections. On the one hand, high data-rate connections are necessary to implement the exchange of information required by smart cities. On the other hand, the implementation of low-cost connections in rural areas will provide services (e-health, improved security, traffic control, etc.) drastically improving life conditions. Connections in moving vehicles are becoming increasingly important for both traditional transportation and autonomous cars, expected soon on market. Interestingly, the same technological challenges are faced in space-observation structures, where demanding performances are needed to better understand the origin and the composition of our world (see Fig. 1).

New devices will have to be installed on **moving targets** (airplanes, trains, etc) and in urban environment. They will have to be **light-weight, low-cost, conformable and very low profile** (for aesthetic or aerodynamic reasons). Furthermore, connections among moving targets and shared services among users require the possibility to choose in which direction to radiate/receive the signals. This means that new communicating devices need to have **beam-scanning/switching capabilities**, usually accomplished by beamforming networks (BFN). Unfortunately, BFN at millimetre waves are currently very bulky, lossy, heavy and not easy to fabricate and integrate: examples are dielectric lenses, parabolic systems, electromechanical scanning planar antenna, phased arrays. Pillboxes are attractive solutions, but still lack the flexibility to arbitrarily shape the radiation pattern, require a dielectric (leading to losses), and are not fully planar.

(a) (b) (c)

Fig. 1 – (a) High speed train (from https://www.raileurope.com/blog/6137-high-speed-rail-europe-asia). (b) Autonomous vehicles exchanging information. (c) Rendering of SKA mid-dish in Africa Space observation antennas (from https://skatelescope.org/).

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Recent promising researches propose metamaterials and metasurfaces as a solution for BFN. They are artificial material and surfaces realized with periodic patterns of subwavelength elements, printed/etched on dielectric substrates. The sizes and shapes of the elements can be slowly modulated to guide the electromagnetic energy at will. This defines a variation of the equivalent refractive index along the surface. In this way graded-index lenses, holographic patterns, and miniaturized circuit components can be produced.

Directive Radiation: Holographic Metasurfaces. An artificial texture printed on a surface modifies the boundary condition enforced on the tangential fields, thus defining an equivalent impedance on it [3]. Radiation features can be obtained through *a spatial modulation of the impedance* [4]: a surface wave can be converted into a radiating wave, and realize a low-profile, low cost device (holographic antennas (Fig. 2a) [5]). On the one hand, this technology is very promising [6], in terms of ease fabrication, light weight and low cost, and conformability. On the other hand, important drawbacks have not been yet addressed: limited flexibility is available for multisource configurations for multibeam antennas. Furthermore, the frequency- dependency of the synthesized impedance can limit ultra-wide band (UWB) applications. Finally, the presence of a dielectric substrate can impact the total losses.

Directive Radiation: Graded-Index Metalenses. Other low-profile planar structures, which can provide directive radiation while also providing beam-scanning, are graded-index metalenses. They are realized by embedding an artificial surface in a parallel-plate waveguide (PPW) (see Fig. 2b) [7]- [9]. The artificial texture is used here in order to synthetize an effective refractive index within the PPW, rather than an effective impedance on the surface (even if the two descriptions are in principle equivalent). By modulating the properties of the texture along the surface one can achieve a modulation of the refractive index and realize a gradient-index lens within the PPW. At the PPW end a flare can be designed to make it radiate. A vast literature exists on lenses for beam scanning (e.g., Luneburg lens), field focusing in certain areas (Maxwell fish eye), and transformation optics [10],[11] to relax shape-related constraints. However, limitations arise from the operational bandwidth of the artificial material. Also, a dielectric inside the PPW introduces losses and radiation mismatches.

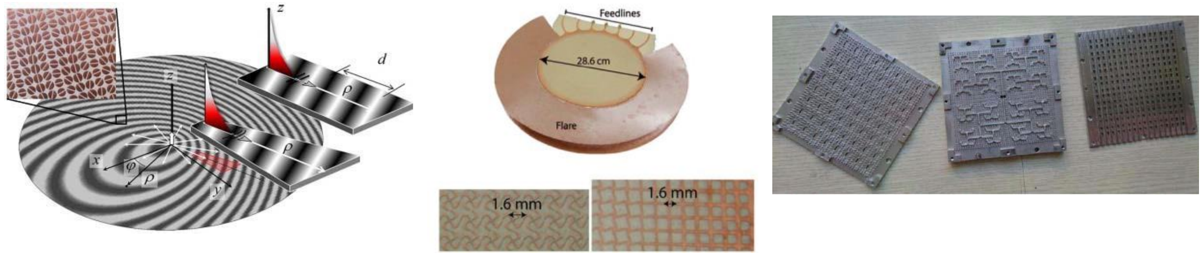
Guided-Waves Suppression: Electromagnetic Bandgaps (EBG) for Gap-Waveguide Technology. Gap waveguide technology (Fig. 2c) is a new contactless technology with low losses (does not require dielectrics) for millimetre- wave range [12],[13]. PPW propagation is suppressed by using EBG structures to guide the power in the desired directions. Since its conception in 2009, the technology is nowadays more and more popular especially for the design of high gain planar antennas, one of the demands of the future 5G systems. Still, a competitive manufacturing technology is a key research topic. EBG structures made with pins (also known as bed of nails) become too narrow and thin at high frequencies.

As summarized in the paragraphs above, metamaterials and metasurfaces are usually narrow band, due to the frequency dispersion of the employed unit cells. Moreover, most of the current prototypes are optimized for one radiation direction, thus preventing beam scanning. Furthermore, current metasurfaces employ dielectrics which usually cause losses, limiting high-power (base stations) and spatial applications.

1.1.2 DESCRIPTION OF THE CHALLENGE (MAIN AIM)

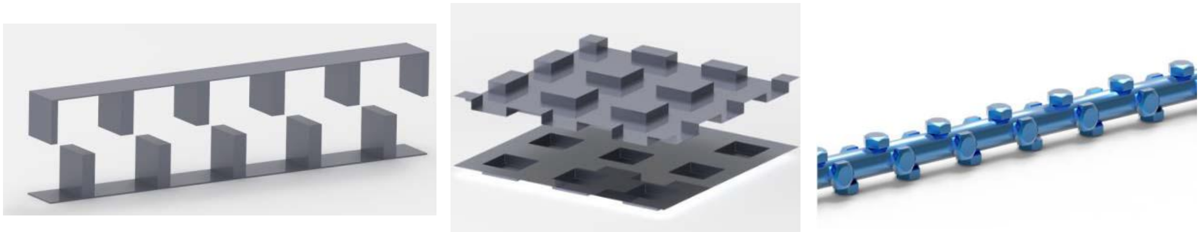
This COST Action has the ambition to unite and promote an international research community proposing innovative solutions to the increasing demand of omnipresent connections in today's society. The Action will investigate the electromagnetic properties of **a new class of artificially engineered surfaces and materials**, and consequently acquire the capability to purposefully design their properties according to the required applications. These artificial materials will allow the implementation of new devices for the future communication infrastructure of connected societies.

The Action will study and develop devices employing **metasurfaces and metamaterials made of periodic cells whose inner structures have higher symmetries**, such as glide or twist symmetries [14] (see Fig. 3). While a periodic structure is invariant after the operation of translation (defining its period), a glide-symmetric structure is invariant after a translation and a mirroring. This is obtained by mirroring a periodic structure and off-shifting the two parts by half a period (see Figs. 3a and 3b). Twist symmetry is the invariance after an operation of translation and rotation (see Fig. 3c).



(a) (b) (c)

Fig. 2 – (a) Holographic antenna from [6]. (b) Graded-index metalens from [7]. (c) Gap-waveguide antenna from [13].



(a) (b) (c)

Fig. 3 – (a). A 1-D glide-symmetric structure, where upper elements are shifted with respect to lower ones by half a period along the periodicity direction. (b) A 2-D glide-symmetric structure. (c) A 1-D twist-symmetric cable from [20].

Despite their simplicity, it has been very recently discovered [15]-[20] that these special symmetries can lead to marvellous properties never found before: **ultra large bandwidth of operation**, significantly **reduced losses** due to dielectric-less propagation, **scanning capabilities**, and **enhanced stopband for Electromagnetic Bandgaps**. These properties can meet the expectation of new communication devices and need to be studied by teams from different backgrounds (physics, electrical engineers, numerical specialists, companies and end users).

Higher-symmetry periodic electromagnetic structures were first introduced in the 70s in connection with metallic waveguides [14]. However, those works had a reduced impact until now and did not open fruitful research lines. Things have changed not only prompted by a series of recent research advancements: *i*) the very recent development of metasurfaces, flat lenses and EBG materials (starting around 2010), *ii*) recent advanced studies on artificial electromagnetic materials (2000-nowadays), but also triggered by the ever-increasing demand for high-quality connections in our modern society. As a result, the new properties of higher-symmetric materials for UWB beam scanning lens antennas and EBG materials <u>have been only recently discovered (2014-2018) and are now beginning to be studied.</u> Due to the great momentum currently existing in this context (confirmed by the success of some sessions organized at the 2017 and 2018 European and American conferences on Antennas and Propagation) it is firmly believed that addressing this problem *in this very moment* can grant a strong scientific and economic impact. Several large industries can be mentioned as end users for the project results, such as European high-speed railway companies, avionic and space companies and agencies (such as ESA and national space agencies). Special activities will be devoted to include the maximum number of interested stakeholders.

Also, in the physics community, a lot of effort is now devoted to the study of periodic structures with special symmetries involving both space and time. As confirmed by the 2016 Nobel Prize in physics for the discovery of “topological insulators,” there is great promise in the application of topology to control waves. Indeed, “artificial topological insulators” for electromagnetic waves are now the subject of intense research, providing potentially useful properties such as the protected confinement of edge waves. These metamaterials may require lattices of time irreversible scatterers (e.g., gyrotropic materials), but solutions using time-reversal invariant scatterers are also explored. Even though these novel media are not currently ready for practical low-cost devices, this Action will devote efforts also to their study. The involvement of end users in the Action will help to investigate and identify possible practical implementations not yet apparent for practical devices.

In conclusion, *right now is the time for Europe to invest on higher-symmetric artificial materials*: Europe must define common strategies and establish shared methods to satisfy future societal needs. The presence in the same network of the main actors of research and development in the field of metasurfaces will stimulate the development of a unified approach toward a new paradigm of technology and its potential application and benefits. This is a crucial moment in time for research on this topic, since the technology is maturing quickly, and this Action will contribute to giving a potential advantage to Europe with respect to other countries such as the USA or China which are continuing to invest strongly in research on artificial materials.

1.2 PROGRESS BEYOND THE STATE-OF-THE-ART

1.2.1 APPROACH TO THE CHALLENGE AND PROGRESS BEYOND THE STATE-OF-THE-ART

As outlined in Sec. 1.1.2, higher-symmetric metamaterials and metasurfaces are promising solutions to overcome limitations in the devices described in Sec. 1.1.1. It has been recently shown that the addition of a **higher symmetry** inside each unit cell of a periodic texture **can suppress the frequency dispersion of the artificial material**. As an example, the structure in Fig. 3b (where the plates are off-shifted by half a period along both periodicity directions) let a wave propagate in between the corrugated plates. The off-shift symmetry between the surfaces enforces a linear phase progression (more specifically, a linear phase constant) with respect to the frequency over a ultra-wide range of frequency. This means that a very stable refractive index can be observed over an UWB, and an UWB pulse can travel between the plates without experiencing distortions. Furthermore, the value of the equivalent refractive index seen by the wave can be tuned by tuning the geometric parameters of the holes. This leads to a possible tapering of these parameters along the surface to synthesize an effective inhomogeneous medium, whose index is stable over a UWB. Finally, the structure is dielectric-less, which allows to avoid the losses due to the dielectric which are the dominant ones at microwave and millimetre waves. Such **an all-metal UWB low-loss structure** is therefore suitable also for high-power and space applications. The inhomogeneous profile of the refractive index can be used to synthesize flat lenses providing scanning capabilities over a wide angle (from -50° to +50° or more [21]).
All-metal lenses offering directive radiation and beam-scanning capabilities, and avoiding the losses due to dielectric materials and to a complex feeding network used in arrays, are the ideal candidates for terminals for satellite communications on vehicles (thanks to their low profile and weight, and their beam scanning features) and for access antennas in next generation communication (indoor environments thanks to their beam scanning capabilities, base stations thanks to their low losses) [22]. With respect to different solutions based on massive Multiple-Input Multiple-Output (MIMO), solutions based on directional radiation obtained with lenses are much simpler, less power consuming and low-cost. For these reasons, they are the best candidates when a large deployment of devices is necessary. The reconfiguration of devices will be an important topic of the Action: it will allow for instance to adapt the radiation diagram to non-line-of-sight scenarios or to cover different areas according to the ever-changing configuration of end users.
Interestingly, the presence of **higher symmetries** also **enhance**s **the frequency width and the attenuation provided by stop-bands** in the material: a new class of wide-band higher-symmetric EBG can then be defined. This allows for a size reduction and a simplification of fabrication techniques of integrated devices whose different components require a high electromagnetic isolation. These devices will again find applications to millimetre-wave communication and radar technology.
These examples prove that currently the most promising way to overcome metasurface and metamaterials limitations by recurring to low-cost techniques is given by the exploitation of higher-symmetries of the periodic lattice and of the shape of the micro-inclusions. Physical explications for all these effects will be a topic of study of the Action, as well as physical bounds leading to simple optimization rules.
As explained, glide and twist symmetries involve *spatial transformations* (translation, mirroring, rotation, see Fig. 3). However, this Activity will pursue novel and possibly unexpected ideas granting a long-term impact on future explorative technologies, even if still on a lower technology readiness level (TRL). Here a few examples are named.
Parity-Time symmetries are sparking new interest in the metamaterial community. They are symmetric under a combined inversion of space and reversal of time (they require the alternation of lossy and amplifying scatterers) - are defined by non-Hermitian Hamiltonians but support waves with either real or complex conjugate frequencies. Dispersive effects of these configurations [23] can potentially lead to devices with enhanced sensitivity and sharper resonances. They can also define topologically protected states (e.g. confined edge modes) robust to perturbations of the structure.
Symmetry breaking can be another effective approach to engineer the dispersive properties of a material. It has recently been shown [24] that a periodic coupling between different lines can be perturbed in order to obtain higher-order (cubic or quartic) degenerate points at the edge of a Brillouin zone, having a higher density of states at degeneracy points and enabling for instance reduced-size resonators and sharper frequency sensitivity.

The challenges faced by this Action lie on several levels, and will require a very diverse network of researchers, due to the innovative kind of technology proposed, and to the variety of possible applications. Activities will range from studying theoretical properties of higher-symmetric materials, to developing analytical and numerical models, discovering new methods for the design of devices and overcoming current technological constraints. The Action is necessary in order to enable the exchange of capacities among researchers from different areas and different backgrounds. This is particularly true with regard to this action, since *several funding opportunities have been obtained in different countries on a national level*. Interactions among groups are the only missing support needed to gain visibility, multiply collaborations, and optimize the researches. In order to ensure an optimal sharing of different areas of knowledge, Short-Term Scientific Missions (STSMs) will be privileged between participants with different expertise. This will be a natural feature of the project, since each Working Group (WG) will include interdisciplinary participants with different backgrounds: physics, engineering and end users.

1.2.2 OBJECTIVES

1.2.2.1 Research Coordination Objectives

The objectives of this Action are the **understanding** of phenomena related to higher-symmetries in metamaterials, the study of their **application**, and their **wide diffusion** from researchers to end users. Specifically, the Action is required in order to:

i) **Develop specific models of higher-symmetric materials to describe and design new materials**, by bringing together scientists with complementary backgrounds (theoretical and applicative). Existing models cannot correctly characterize higher-symmetric materials and new tools need to be developed for analysis and design.

ii) **Designing new radiating systems by exploiting higher-symmetric geometries** to achieve performance beyond the state-of-the-art in terms of *beam-scanning capabilities*, *operational bandwidth*, *losses* in *different technologies* such as slotted SIW, open gap waveguides, planar PCB, 3-D printable materials for artificial lenses. Relevant specifications will be made available by interacting with the companies participating to the Action.

iii) **Designing new guiding-wave devices by exploiting higher-symmetric geometries** to achieve performance beyond the state-of-the-art in terms of *insertion losses*, *operational bandwidth*, *isolation*, *losses* in *different technologies* such as SIW filters and resonators, gap waveguides, planar PCB, 3-D printable materials. Relevant specifications will be made available by interacting with the companies participating to the Action.

iv) **Reaching stakeholders to communicate on higher-symmetry materials.** The topic is new and there is very limited information among stakeholders. The Action aims to make them understanding the potential of these kind of artificial materials for communications.

1.2.2.2 Capacity-building Objectives

The network will have important capacity-building effects among its participants thanks to their different background of competences. The network will:

i) **Avoid fragmentation of research and share negative results** among different researchers so that efforts will be joined rather than competitive. The Action will avoid duplicating efforts on the same subjects and will prevent from time-consuming modifications of planned actions.

ii) **Enable researchers to implement their results by accessing a shared network of infrastructures for fabrication/measurements.** A list of available measurement/simulation facilities, together with details on their availability for activities of the Action (period of the year, technical staff availability, access procedures) will be on the Action website. The fabrication/measurements will be preferably done in the framework of a COST short mission to directly train the researchers involved to fabrication/measurement activities.

iii) **Provide Early Career Investigators (ECI) with training** in the framework of doctoral schools on state-of-the-art offered by academia and industry partners (currently non-existing on this subject) and short missions *(measured by the number of ECI involved in STSM and management responsibilities).*

iv) **Promoting a balanced female/male environment.** The ratio female/male will be increased when extending the Action to new participants in order to achieve a balanced environment. This balance will be kept in the scientific and dissemination activities to implicitly communicate to the public on this subject (*measured by the evolution of the ratio female/male).*

v) **Extending the network beyond research-intensive countries.** The extension of the Action will be performed with special care toward COST Near-Neighbour Countries (NNC) and Inclusiveness Target Countries (ITC) *(measured by the number of ITC and NNC participants joining the Action).*

2 NETWORKING EXCELLENCE

2.1 ADDED VALUE OF NETWORKING IN S&T EXCELLENCE

2.1.1 ADDED VALUE IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

This network will initiate a new European research environment in the field of artificial materials for communications. Of course, no other European or international actions are specifically focused on higher-symmetric metasurfaces for the applications proposed by this Action, since these structures have only been recently discovered. On the other hand, several European actions, mainly individual ones, have been funded to study metamaterials and metasurfaces. Being individual or small partnerships grants, the activities developed have a limited interdisciplinarity and a narrower application focus. However, they show a rich research community interested in the activities in this COST Action, and will help to extend the Action to new participants. Among past grants, the 2016-2018 Marie Curie Individual fellowship “Topological-Plasmonics” is devoted to the development of new metasurfaces based on topologically protected modes. The COST MP0702 (started in January 2008) “Towards Functional Sub-Wavelength Photonic Structures” was again focused on metamaterials, but for a different frequency range (optics) and applications.

Connections will be pursued with existing actions, both COST and of other kind. The FETOPEN NANOARCHITECTRONICS aims at the development of reconfigurable metasurfaces based on wave-matter interactions at nanoscale, and addresses a vast scale of frequencies, but does not focuses on symmetry-related effects. The ERC TOPOLOGICAL aims at the study of novel topological physics and applications introduced by Berry phase. While the present COST Action covers a much broader range of symmetries and frequency ranges, possible forms of collaborations will definitely be envisaged. Several other European projects are focused on the study of topological properties of matter for electronics or acoustic problems rather than electromagnetics (such as TopoMat, TOPP, etc.). Despite treating different physical domains, participants to these projects will be invited to join the network or will be involved as external researchers. Another connection will be created with the ITN-EID network REVOLVE (started January 2017), working on radio technologies for space communications. Exchanges of practices, technologies and results will be carried out, with the aim of the institutions that are part of the network joining this Action. The COST IRACON CA15104 “Inclusive Radio Communication Networks for 5G and beyond” (started March 2016), more focused on the development of Information Theory for new generation communications. Their researches can provide useful inputs to determine the specifications of our devices.

The network will seek the support of the main European electromagnetics association: the European Association of Antennas and Propagation (EurAAP) and the European Microwave Association (EuMA). The European School of Antennas (ESoA, a PhD school network of the EurAAP, http://www.esoa-web.org/) already includes a one-week course on metasurfaces applied to antennas and a course on periodic structures. Possible partnerships will be sought with the EuMA, currently creating its own PhD school network. On an international level, collaborations will be sought with the Institute of Electrical and

Electronic Engineers (IEEE), the Institute of Engineering and Technology (IET) and the International Union of Radio Science (URSI) associations.

2.2 ADDED VALUE OF NETWORKING IN IMPACT

2.2.1 SECURING THE CRITICAL MASS AND EXPERTISE

Participants having a diverse scientific and geographical background will be an essential feature to enable research in higher-symmetric metasurfaces. Due to the novelty of this subject, it is not yet possible to define independent activities. Interactions among researchers are necessary to advance in meaningful research directions. The partners in the initial network of proposers for this Action were selected by including research groups having already experience with metamaterials with higher symmetries, mainly in the electrical engineering domain. Since the topic is rather new, a large part of the international community working on the subject is represented. Furthermore, other partners are internationally well-known for their achievements in metamaterial and metasurface research, both in the engineering and in physics community. They will secure the capability to develop higher symmetric configurations in different branches of research in artificial materials, on the basis of their experiences. Current researches on the topic suggest that new interesting results are found by interacting with researchers working on different aspects of metamaterial theory. Finally, partners with applied backgrounds (antennas for communications, for biomedical and e-health applications, for radio-astronomy) coming from companies and research institutions will provide their experience about application-related topic to assure the transfer of knowledge from the theoretical research groups to the application-oriented institutions.
Further expansions of the network will be done by respecting this balance among different backgrounds. The advancement of the activities will suggest the better balance among disciplines during the development of the Action.

2.2.2 INVOLVEMENT OF STAKEHOLDERS

The most relevant stakeholders will be involved in the Action with different approaches. The accomplishment will be measured by the number of relevant stakeholders who successfully join the Action.

i) Scientists. They will be reached at special sessions organized in symposiums and personally invited to regular meetings if their research interests coincide with the subjects presented at the meeting. The invited scientists will be selected on the basis of the personal networks of the participants and on bibliographic analyses done in the framework of the research activities.

ii) Companies and end users. Already five companies were part of the network of proposers for this Action, which proves the interest of private sector in this research. Other companies and end users of devices designed with higher-symmetry materials will be reached at exhibitions, when feasible together with speaking opportunities, organized on a European or a national/local level (companies for communications, railway and flight, domotics, e-health, security, etc). Note that companies can be regarded as end-users of some of the devices under study (access antennas, antennas for vehicles), but other end users will be defined according to the application: final customers and doctors for e-health and domotics devices, radio-astronomy institutes for antennas for radio telescopes.

iii) Agencies and organizations. Several organizations will be interested to follow the activities of the Action. For example, the IEEE, the IEE, the URSI, the European Space Agency (ESA) and national space agencies. Many organizations can be identified in the space-observation sector (NASA, ALMA, SKA, e-Merlin, MPIFR, FAST, MeerKAT), and will help outreach activities toward the general public. All these stakeholders will be contacted thanks to the personal contacts of the participants.

iv) Policy-makers. National research-funding agencies will be invited to seminars and workshops during round tables. As said in Section 1.1, the issues of interest of the Action are related to the development of research policies which favour young researchers, gender parity, and benefit society as a whole. As said in Sections 1.2.2.2 and 2.2.1, the Action expansion to new participants will increase the female/male ratio, keep a very young network and increase the participation of ITC and NNC. This will be accomplished by giving females, ECI and ITC visible roles in the Action management.
The presence of stakeholders representing different applications (e.g., long-range communications for

on-vehicle applications, short-range for e-health and domotics companies, different frequency ranges) will be beneficial to the transfer of knowledge from theoretical groups toward application. The theoretical results will certainly offer several different opportunities, as is confirmed in the first stage of research on this subject, and each application field will stimulate a possible interaction to exploit a given physical phenomenon.

2.2.3 MUTUAL BENEFITS OF THE INVOLVEMENT OF SECONDARY PROPOSERS FROM NEAR NEIGHBOUR OR INTERNATIONAL PARTNER COUNTRIES OR INTERNATIONAL ORGANISATIONS

The expansion of the Action will be done having as a priority the inclusion of members from near neighbour and international partner countries by exploiting ongoing collaborations of Action participants with these countries. Opening new collaborations have shown in the recent past always to bring new ideas to the topics and allow for obtaining results beyond the expectations. The private sector of near neighbour countries will be included in order to improve the knowledge transfer toward companies and to contribute to the development of the technological tissue of the country.
As it will better explained in Sec. 3.2.2, the impact of the Action will also be dependent on the inclusion of international organization such as ESA and CERN, space-observation organisations, which place antennas and microwave devices at the core of their activities, and whose interest lie perfectly in line with the topics of this Action. Finally, policy-makers such as research funding agencies, spectrum-usage regulation agencies and regulatory agencies for electromagnetic exposure will be involved starting from the first meetings. The exchange will be two-fold: policy maker will guide the direction of the activities based on existing policies and the Action will stimulate innovations in policies if necessary according to the research results (see the planned White paper in Sec. 3.2.2, 4.1.1 and 4.1.4).

3 IMPACT

3.1 IMPACT TO SCIENCE, SOCIETY AND COMPETITIVENESS, AND POTENTIAL FOR INNOVATION/BREAK-THROUGHS

3.1.1 SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS (INCLUDING POTENTIAL INNOVATIONS AND/OR BREAKTHROUGHS)

In the past 8 years, since the concept of metasurfaces was introduced, technology has advanced from theoretical designs towards real implementable devices. Technologically leading companies are beginning to collaborate with universities to explore their practical possibilities. Small start-up companies have been founded to apply to practical problems what has been done in research centres. This not only illustrates the potential of this technology, but also indicates that the field has reached the stage where its potential can be exploited. The technology of higher-symmetry metasurfaces is the missing element which can fill in the gap between laboratory prototypes and mass production, and this justifies the need for a COST Action going from physicists to end users.
From this point of view, the short-term impact of higher symmetries on the field of metasurfaces is undoubtedly already shared in the scientific community, for example testified by the success of sessions on these topics at the 2017 and 2018 conferences on Antennas and Metamaterials. This scientific impact will be significant in different communities: physics (due to the extraordinary properties of electromagnetic waves propagating in these materials), antenna and microwave engineers (due to the marvellous properties of these novel devices), and numerical scientists (due to the challenges in the modelling of such low-profile and strongly-coupled surfaces).
A **long-term socioeconomic impact** is expected **in the new IoT environment**. IoT will likely be a revolution in the paradigm for communicating devices of the next decades. In fact, the increasing demand of omnipresent connections required by the development of IoT has stimulated a revolution in terms of device technologies. The Ka frequency band seems to promise higher data rate and shared connections for mobile targets (e.g. train, airplanes) and urban connections (preliminary studies confirmed the feasibility of 28 and 38 GHz urban connections) [1]. At the same time, satellite communications are also moving toward higher frequencies (17.7–21.2 GHz for transmitter and 27.5–31 GHz for receiver) to grant higher data rates [2]. In this framework, the European “5G PPP” program, a 1.4 billion Euro initiative of the European ICT industry and the European Commission, aims

at “rethinking the infrastructure […] that will provide ubiquitous super-fast connectivity.” Countries outside Europe are advancing fast on the development of the network required for this level of connectivity. However, as explained, ***conservative technologies such as reflectors or phased arrays will be the bottleneck of communicating standards and will not enable a capillary diffusion of devices*** (and then of ubiquitous services) in smart cities [2]. A new technology is necessary, having wide bandwidth, leading to light weight, low cost, conformable and very low profile devices, and providing beam switching. Higher-symmetry metasurfaces have the potential to respond to all the mentioned challenges: ultra-wide band, low-loss and potentially high-power (since the energy propagates in the air) [17]-[19], low profile and conformable [6], providing 1D beam switching at a low cost and low weight, and with a low-power consumption (the antenna being passive and only switchers being necessary for beam selection) [7]-[9].
The realization and measurement of demonstrators in the Ka band with these features will have a major economic and societal impact (increasing the quality of the connectivity in our societies with the development of communications, e-health, improved security, etc). These results will surely stimulate the creation of start-ups and/or be beneficial to start-ups already existing in the sector.

3.2 MEASURES TO MAXIMISE IMPACT

3.2.1 KNOWLEDGE CREATION, TRANSFER OF KNOWLEDGE AND CAREER DEVELOPMENT

Knowledge creation is regarded as the first aim of the activities of the Action, since it is the main contribution to the achievement of innovating advanced solutions. The transfer of knowledge toward students will be supported by organizing summer PhD schools (see transverse working group TWG3) and when possible short courses at international conferences and at local events (not yet detailed in the Gantt diagram). Part of the material developed for the training events will be available on the website of the Action and participants and colleagues will be encouraged to integrate it in existing Master programs at each University. The transfer of knowledge between disciplines will also be performed by requesting that a percentage of the short missions be done among partners from different disciplines (this percentage will evolve together with the composition of the network). The same will be accomplished regarding the transfer of knowledge from theoretical to applied groups.
The career development of each non-permanent participant (PhD candidates, post- doctoral researchers, etc) will be an important axis of the activity. The PhD schools will contain classes on soft skills and their use in different fields of expertise. This will be done by involving the departments of professional orientation of different Universities and of human resources of companies participating to the action. All PhD students involved in missions will receive a financial aid to partial cover their participation to a following Action meeting to present the results obtained. This will help to include them in the network and to develop several soft skills related to presenting research results and interacting in a symposium. This will also assure the transfer of knowledge among the participants to the Action. A department of professional orientation of one institution per country will be chosen to offer information on post-doctoral professional orientation to PhD students interested to the job market of that country. One industrial partner will participate to the orientation of students interested to join the private sector after his/her PhD program.

3.2.2 PLAN FOR DISSEMINATION AND/OR EXPLOITATION AND DIALOGUE WITH THE GENERAL PUBLIC OR POLICY

Dissemination toward scientists. Results will be disseminated through publications in Open-Access international journals (all publications will also be on ArXiv), conferences, and annually organized workshops at conferences. Special sessions will be organized in two conferences every year (one in Europe, one in America, such as the *IEEE Antennas and Propagation Symp.*, the *European Conf. Antennas and Propagation*, the *European Microwave Week*, *Metamaterials Congress*, *META*, *Int. Conf. Metamaterials*, *Photonic Crystals and Plasmonics*, to cite a few). PhD students collaborating in the Action will be encouraged to present their work twice per year in one of these conferences. Grants to attend the conferences will be offered to motivated students from ITC, selected by the Management Committee. A fraction of the grants will be open to students that are not part of the Action, thus helping the visibility of the network and its possible expansions. *Quantification: number of publications (at least one per participant per year), number of special sessions organized (estimated public: 70-100 at each special session, according to the conference), number of grants assigned to ECIs.*
Exploitation plan outside academia Participation to exhibitions on a European or a national/local level will be planned. Companies for communications, railway and flight, domotics, e-health, and security product will be targeted and also invited to participate in the periodic meetings. A coherent

exploitation plan will be prepared by an elected responsible of dissemination (chosen among the participants from the private sector). The plan will foresee the participation of national agencies, regulatory and technical organizations to expand the network toward companies and to gather a critical mass needed to propose European projects in the areas of "Industrial leadership" and to address specific "Societal challenges". The aim will be to bring to commercialization the prototypes developed in the research activities. The Exploitation coordinator will make sure that in relevant projects a Consortium Agreement (CA) is signed in advance, defining internal management rules of the consortium: responsibility/commitment of each participant, confidentiality, intellectual property management, patents/licenses development, etc. **The companies involved** in the Action will benefit of a priority access to the technology developed in this context, leading to the first patents in the sector and to a considerable advantage on competitors. Furthermore, companies will benefit of young researchers (e.g., PhD candidates) which will be highly skilled at the end of their academic experience; they will have been formed in the COST schools (where the same companies will have participated) and in research exchanges. Also, companies will benefit of a direct contact with funding agencies (invited to meeting, see Sec. 3.2.2) and with possible partners in academics to access European funding. *Quantification: number of new participants from companies joining the Action.*
Dissemination toward policy-makers and agencies. Policy-makers and agencies will be invited to the Action's regular meetings to discuss the necessities of research activities and to push for best practices in the research worlds on the basis of the experience of the participants. A White paper will be prepared with recommendations and guidelines on the common features of higher-symmetry metamaterials. At each COST meeting, market studies will be presented to prove the socioeconomic impact of the technologies presented. Prototypes will be accessible to associations on health related to human exposition to electromagnetic waves (after signing a relevant CA for confidentiality reasons). They will independently verify the positive effect on public health (radiated powers from radio stations will be lower thanks to a better spectral efficiency). While disseminating scientific results to the public, ECIs will also contribute to the public debate about the role of research and research funding in the future society, gender balance and diversity in research, by addressing relevant stakeholders and agencies. *Quantification: number of policy makers joining the Action or attending the meetings.*
Dissemination toward high/school students and general public. Accounts on the most popular social networks will be used to disseminate the results and promote activities. Regular posts will describe the research, training activities, patents, social impact. The impact of results will be made clear to a general audience will understand their importance. Depending on the impact of each result, this information will be re-distributed on newspapers and on the social network accounts of the institutions and researchers participating in the network. As an example, videos summarizing research activities and training courses for non- specialized audience will be put on-line, and will be available on the Action website. *Quantification: number of videos uploaded per semester, number of views of the online material.*
Intermediate local exhibitions will be organized in various countries by each of the teams, on the occasion of some of the scientific meetings.

4 IMPLEMENTATION

4.1 COHERENCE AND EFFECTIVENESS OF THE WORK PLAN

4.1.1 DESCRIPTION OF WORKING GROUPS, TASKS AND ACTIVITIES

The Action will be developed by supporting the following activities among participants:

- **STSM**, privileged among ECIs and among participants having different research interests, and **grants** for ECI participation to conferences,
- participation to the **periodic meetings**, common for all the COST participants,
- organization and participation to periodic **training activities**,
- **sharing of resources available on the website** of the COST Action, resuming all the current investigations of the different participants and **sharing of computation, fabrication and measurements facilities**,
- **collaborative** preparation of **dissemination** activities.

All these activities will be organized in 6 working groups (WGs). Each group, managing multiple sub-activities, will be characterized by a main topic. Due to the close relation among many sub-activities of different WGs, different activities could merge into unified lines.
Management Committee: The MC will manage the network organization with specific attentions to

i) its expansion, *ii)* dissemination and exploitation activities, *iii)* gender- and minority-related issues, iv) final outputs concerning the whole network. These outputs will be **1)** a road-map paper on symmetries in artificially engineered materials (with contributors from inside and outside this COST Action); **2)** a white paper about capabilities of this new technology, short description of results, design guidelines and limitations. It will be addressed to end-users and stakeholders contacted during the Action (and others which could not be contacted, if any). Risks related to management activities are summarized in a Table in Sec. 4.1.3.
Management meetings: The MC will meet twice per year. All the WGs and the TWGs will schedule their meetings at the same time for a better coordination. Meetings will be organized preferably in ITC countries. To help participants with families, targeted information will be provided on accommodation and childcare. Phone/skype meetings will be arranged for the MC and each WG/TWG around every 8 weeks. All the WG will proceed to task assignments (or re-assignments) during these meetings.

WG1 – HIGHER-SYMMETRIC WAVES: DISPERSIVE ENGINEERING

WG1 will manage activities focused on wave propagation **dispersive properties** inside materials having higher symmetries. The propagation of a wave will be described by its phase/group velocities. Their frequency dependence determines its *frequency dispersion*, while its dependency on the direction of propagation will determine its *spatial dispersion*. Absence of dispersion consists in constant velocities, a rare condition desired in UWB operation conditions. As previously explained, higher-symmetric materials provide absence of dispersion on a UWB, thus motivating their interest. In order to perform these studies, new fast and accurate modelling tools may be required.
Objectives. This WG1 will relate dispersive properties with relevant symmetries and explain them in terms of degenerate points (double modes at a coincident frequency) and symmetry properties of the modal fields. Different configurations of possible interest for the WG2 and WG3 will be studied. They will provide different **polarizations**, **anisotropic** or **non-reciprocal effects**. The possibility to engineer desired frequency dispersions by introducing suitable symmetric/asymmetric conditions in periodic materials will be also the topic of WG1. This will pave the way to ***filtering materials*** **controlling wave propagation features at each frequency and for each propagation direction**.
Tasks. T1: Selection of geometries with interesting properties and applications, and classification according to their Technology Readiness Level (TRL); **T2**: dispersive analyses ; **T3**: preparation of experiments for validation, publication and dissemination of results.
Activities. *STSM* involving participants with physics and engineering background for capacity/building and interdisciplinary research; *special sessions organized* in physics and engineering conferences for the maximum dissemination of the Action; *periodic meetings.*
Milestones. M1: definition of possible new participants to be invited in the Action (once per year); **M2**: definition of case studies and their TRL level; **M3**: study of dispersive properties and proposal of applications; **M4**: results of experimental tests; final reports and publications

WG2 – HIGHER-SYMMETRIES TO DESIGN RADIATING DEVICES

The non-dispersive features of higher-symmetric materials are beneficial for UWB communication since they avoid a distortion of wideband pulses. For this reason, WG2 will manage the activities related to the design, the optimization, the fabrication and the measurement of radiating devices based on higher-symmetric metamaterials or metasurfaces. According to the description done in Section 1.3.1, the main investigations will focus on several kinds of antennas.
Objectives. *Holographic antennas*. Possible effect of higher-symmetric configurations on beam-squinting reduction will be evaluated through a semi-analytic approach. The use of all-metal structures, where required impedance variations are obtained by means of higher symmetries, will be explored. Higher symmetries for anisotropic and dispersive effects will also be explored.
Graded-index metasurfaces. Different geometries of scatterers embedded in a PPW will be used in order to assess the physical limitations in terms of available effective refractive index, losses and bandwidth. Since PPW lenses are inherently flat, radiation will be directive along one direction only. The coupling with other radiating devices providing directivity along the orthogonal plane will be studied in order to preserve the performance of higher-symmetric metasurfaces.
Space-observation lenses. Higher-symmetry metamaterial lenses can bring great advantages for telescopes, such as multibeam discrimination of different directions in the sky associated with a given pixel in the bolometric detector. Furthermore, metasurfaces could achieve high-gains and replace the use of arrays in radio astronomy, usually leading to high power consumption.
Conformal antennas. they will be explored with holographic metasurfaces. Twist symmetry of the impedance modulation could lead to interesting UWB radiating effects.
Fabrication and measurements of prototypes will be performed in the laboratories of the relevant

institution, if possible, or done outside with individual funding. If problems arise in a specific facility, other institutions will share their equipment on the basis of solidarity among the partcipants.
Tasks. T1: Definition of required performance for each technology: definition of best strategies; **T2**: design and optimization of devices (if necessary, together with WG1); **T3**: prototyping and measurements; **T4**: publication and dissemination of the results.
Activities. STSMs involving academics and companies for capacity/building and interdisciplinary research; workshops at antenna and astronomy conferences and visits in companies (possibly not yet part of the Action) for the maximum dissemination; periodic meetings.
Milestones. M1: definition of possible new participants to be invited into the Action (once per year); **M2**: definition of case studies and their TRL level; **M3**: quantification of the achievable performances; **M4**: results of experimental tests; **M5**: final reports and publications.

WG3 – HIGHER-SYMMETRIES FOR GUIDED-WAVE COMPONENTS

The WG3 will work on applications of higher-symmetric structures that guide confined waves. The relevant applications will be frequency- or spectral-domain filters, guided-wave lenses, modified waveguides, or metamaterial elements to be embedded in antenna devices. For the latter designs, interactions with WG2 will be stimulated for a co-design of the guiding and the radiating parts.
Objectives. *Electromagnetic bandgap (EBG) higher-symmetric materials.* Glide-symmetric structures have recently demonstrated the ability to produce low-cost gap waveguide technology. Glide-symmetric configurations have enhanced bandgaps with respect to conventional structures, and are much more robust with respect to geometrical dimensions. Consequently, the manufacturing cost is dramatically reduced. The development of low loss, low cost complex feed networks and components to be used in advanced array systems will be one of the objectives of this WG.
Metamaterial elements for integrated circuits. Planar antenna technology is among the most common solution for integration with monolithic circuits. Its performance can be improved if metamaterial elements are embedded in the design as transmission lines, geometric defects or modified ground planes. The use of higher-symmetric metamaterials/metasurfaces with exotic propagating/band-gap properties will be studied for embedding in several kinds of printed antennas.
Tasks. T1: Definition of required performance for each technology, definition of best strategies; **T2**: design and optimization of devices (if necessary, together with WG1); **T3**: prototyping and measurements; **T4**: publication and dissemination of the results.
Activities. STSMs involving academics and companies for capacity/building and interdisciplinary research; workshops at microwave conferences and visits in companies (possibly not yet part of the Action) for the maximum dissemination; periodic meetings.
Milestones. M1: definition of possible new participants to be invited into the Action (once per year); **M2**: definition of case studies and their TRL level; **M3**: quantification of the achievable performances; **M4**: results of experimental tests; **M5**: final reports and publications.

WG4 – MODELLING OF HIGHER-SYMMETRIES

The study of properties of higher-symmetric metasurfaces require fast and accurate modelling tools to ***i)* predict the behaviour** of the structure and ***ii)* optimize a final prototype**. Unfortunately, two major problems are faced. At first, these materials share with ordinary metamaterials the presence of a **large number of geometrical details at different scales** (e.g., see Fig. 3a), leading to large and ill-posed problems. Furthermore, in order for the symmetry to be effective, a **very short distance is necessary between corresponding elements of the geometry** (e.g., between the surfaces in Fig. 2, a very thin gap is required to achieve a suitable range of effective refractive index). These small gaps and details are difficult to model in common numerical approaches (Finite elements, method of moments, etc).
Objectives. New circuit models will be developed. **Green's functions methods** will be studied for higher-symmetric layered methods, to avoid the discretization of the layered configuration, described by the Green's function. Regarding the complete metasurface, methods as the **Fast Multipole and multiscale approaches** can be investigated with *ad-hoc* formulations for higher symmetries.
Tasks. T1: Definition of the required method according to the needs of the other WGs; **T2**: definition of best researchers in numerical and analytical methods to extend the Action; **T3**: code development; **T4**: testing on benchmark structures and on structures studied by the other WGs, **T5**: publication and dissemination of the results.
Activities. STSMs involving academics and companies for capacity/building and interdisciplinary research; workshops at microwave conferences and visits in companies not being part of the Action;

periodic meetings.
Milestones. M1: definition of new invitations to the Action (in years 1 and 2); **M2**: definition of case studies and their TRL level; **M3**: study of devices and quantification of the performances; **M4**: results of experimental tests; **M5**: final reports and publications.

WG5 – DISSEMINATION OF RESULTS

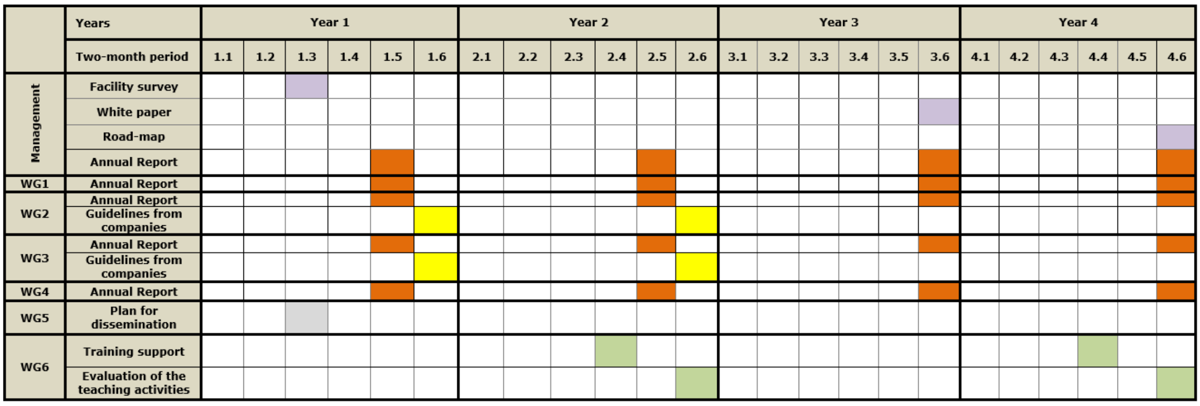
Objectives: Managing the dissemination of the results of the Action, the expansion of the Action, and risks according to Section 2.2.2 and 3.1.4. The Science Communication Manager will be the leader of this WG.
Tasks. T1: Selecting conferences for special sessions/workshops using suggestions of WGs (a 4-year plan will be done and constantly updated); **T2**: selecting participants to join the Action and inviting them at meetings using suggestions of WGs; **T3**: managing participation to exhibitions; **T4**: monitoring the overall publication activity.
Milestones. M1: special session/workshop organizations; **M2**: participation in exhibition/outreach, scientific publications, **M3**: Network expansion.

WG6 – TRAINING ACTIVITIES

Objectives: Schools for the PhD students and ECIs of the Action will be organized annually. Two schools can be shared with the European School of Antennas (ESoA), funded by the European Association of Antennas and Propagation (EurAAP). A school, specifically on higher symmetries, will be organized with the **Eu*M*A** organization. At least one short course will be planned at a main conference on metamaterials, antennas and microwaves in Europe. For every STSM a seminar by the guest will be planned for students and young researchers of the host institution (on scientific, societal, or research-policy subjects).
Tasks. Defined at regular TWG3 meetings, five months before each school (see GANTT diagram) to finalize the activities and the training supports of the closest school and organize the later ones. **T1**: definition of aims of the schools (scientific and transverse skills, clearly visualized in the advertisement) and of the training material required to accomplish the expected training progress. **T2**: Definition of parameters to measure the course success. **T3**: Self-evaluations and final evaluations preparation. Transverse skills and their evaluation methods will be defined with the department of researcher carrier development in the leading institution of the COST, having several years of expertise in these problems across many disciplines. Phone meetings two months before and four months later each school will help its final organization and evaluation, respectively.
Milestones. M1: Definition of skills to be acquired at each training event; **M2**: preparation of training support; **M3**: evaluation of grants submitted for financial help to attend; **M4**: evaluation of the activities.

4.1.2 DESCRIPTION OF DELIVERABLES AND TIMEFRAME

The planned deliverables will be prepared from each working group and transverse working group in the framework of each meeting and submitted shortly after, according to the timeframe shown below. Annual reports of the Management WG describe the research activities, the expansion of the network, dissemination and exploitation activities, gender- and minority-related issues (these points will be evaluated according to the measures and targets presented in Section 1.2). The training support for each school (notes, videos, computer codes, interactive Q&A for auto-evaluations, detailed plans for practical experiences) will be available to the whole network in advance of each school in order to coherently organize the overall event.



The timeframe of the Action is fully illustrated in the Gantt diagram in Sec. 4.1.4, where the schedule of all the activities and the milestones described in Sec. 4.1.1 is detailed.

4.1.3 RISK ANALYSIS AND CONTINGENCY PLANS

The risk management and the contingency plan will be managed by the Management Committee, receiving WG feedbacks and discussing risks and solutions. This is detailed in Sec. 4.1.1.

Priority	Technical Risks	WG	Proposed mitigation measures
High	**Losses have a stronger impact than expected**	1,2,3	Different trade-off losses/bandwidth will be sought according to the application/service of study (**impact: medium**).
High	**Dual polarization cannot be achieved**	1,2,3	Different strategies, possibly more conservative, will be explored (**impact: medium**).
Medium	**A given technological choice or research approach seems not fruitful**	1,2,3	Other external experts in that technology will be contacted. If the issue is confirmed, efforts will be redirected toward alternative technologies or approaches (**impact: low**).
Medium	**Prototypes are too expensive**	2,3	Funding from different European/national projects will be mutualized, if necessary, among participants. New participants could be included if relevant (**impact: medium**).
Medium	**Numerical modelling is too complex and not advantageous over existing methods**	TWG1	Simplified approaches will be sought in order to speed up computation times. New participants will be included which can help to achieve the result (**impact: medium**).
Low	**Prototypes bandwidth is narrower than expected**	1,2,3	Different topologies will be investigated. Applications/services compatible with the obtained bandwidth will be addressed (**impact: medium**).
Low	**Difficulties with fabrication and/or measurements**	1,2,3	New participants will be included which could help to achieve the results ((**impact: high**)).
Priority	**Management Risks**	**WG**	**Proposed mitigation measures**
High	**Brexit occurs during the action** (*direct responsibility of MC*)	1	Directives from the COST Association and UK will be followed. If necessary, alternative funding will be used keep UK participants in the network (**impact: medium**).
High	**Issues organizing courses/ special sessions/workshops**	All	Alternative conferences will be identified. (**impact: low**).
Medium	**Unexpected need of software, manufacturing/measurem. facilities**	2,3 4,5	Solidarity among participants will be used. Other institutions will be invited (**impact: medium**).
Medium	**An ECI leaves the academic sector**	2,3 4,5	Only one of initial proposers is non-permanent. If more non-perm. join the Action (pursued to balance permanents/non-permanents) other colleagues will be invited (**impact: medium**).

4.1.4 GANTT DIAGRAM

The GANTT diagram below shows the network implementation with details of tasks and milestones of each WG and TWG. Variations due to the results of the activities will be approved by the MC.

	Years	Year 1						Year 2						Year 3						Year 4					
	Two-month period	1.1	1.2	1.3	1.4	1.5	1.6	2.1	2.2	2.3	2.4	2.5	2.6	3.1	3.2	3.3	3.4	3.5	3.6	4.1	4.2	4.3	4.4	4.5	4.6
Management	MC meetings																								
	White paper																								
	Road-map																								
	Annual Report																								
	STSM																								
WG1	WG1 meetings																								
	Convened sessions																								
	Tasks	1	1	1	1,2	1,2	1,2	2	2	2	2	2	2	2,3	2,3	3	3	3	3	3	3	3	3		
	Milestones					1		2				1						1	3					4	
WG2	WG2 meetings																								
	Convened sessions																								
	Tasks	1	1	1	2	2	2	2	2	2,3	2,3	2,3	2,3	3,4	3,4	3,4	3,4	3,4	3,4	3,4	3,4	4	4	4	
	Milestones					1,2						1		3				1				4		5	
WG3	WG3 meetings																								
	Convened sessions																								
	Tasks	1	1	1	2	2	2	2	2	2,3	2,3	2,3	2,3	3,4	3,4	3,4	3,4	3,4	3,4	3,4	3,4	4	4	4	
	Milestones					1,2						1		3				1				4		5	
WG4	WG4 meetings																								
	Convened sessions																								
	Tasks				1,2	1,2	1,2	3	3	3	3,4	3,4	3,4	3,4,5	3,4,5	4,5	4,5	4,5	4,5	5	5	5			
	Milestones					1		2				1				3				4			5		
WG5	WG5 meetings																								
	Dissemination plan																								
	Tasks	1,2			3	4		1,2			3	4		1,2			3,5	4,5	5	3,5	5	5	5	5	
	Milestones						1	2,3	4				1	2,3	4				1	2,3	4	1		2	
WG6	WG6 meetings																								
	Training events																								
	Evaluation of the teaching activities																								
	Tasks	1,2,3	3		3			1,2	3		3			1,2	3		3	1,2				3		3	
	Milestones	1	2,3			4		1,3	2			4		1,3	2			1,4		3		2			4

Reports: Annual reports describe the research activities, the expansion of the network, dissemination and exploitation activities, gender- and minority-related issues (these points will be evaluated according to the measures and targets presented in Section 1.2).
Events: Convened sessions are arranged once per year (twice if possible according to the available conferences) at one or two different conferences (expected in spring and in summer). Workshops will be arranged by WG2 and WG3 alternating different conferences (in spring and summer too). STSMs will be possible during the whole Action. A training event is planned every year (two PhD schools with ESoA and Eu*MA* and two short courses at a conference).

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