COORDINATING EUROPEAN RESEARCH ON MOLECULAR COMMUNICATIONS

D4.1 Expert working group report

Author (PARTNER)

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1. Introduction

This deliverable reports on the progress of the strategic activities and the definition of the expert working group.

This document illustrates the activities, which have been undertaken within the first year of CIRCLE activities to identify the main expert working groups. Here, the considered data science oriented methodology is presented with the aim of both objectively identify the expert working groups and, based on their research outcomes, to provide a taxonomy for molecular communications and to derive the scientific roadmap. Finally, an interconnected list of the most active research group in the molecular communication field is presented.

The activities related to strategic activities to the achievement of all the CIRCLE objectives, reported in what follows for the readers' convenience:

- **O1** Harmonise heterogeneous islands of research in Molecular Communications across Europe by providing a structured research agenda through the collaborative specification and continual refinement of a research roadmap that will be developed within CIRCLE project.
- **O2** Stimulate guided learning for young researchers entering the area of Molecular Communications, through improving efficiency of knowledge acquisition in key disciplines.
- **O6** Reduce the barriers for entry into the area of Molecular Communications for high tech SMEs through the collaborative specification and continual refinement of an industry engagement roadmap.

The structure of this deliverable is as follows: We first provide an overview in Sec. 2. The proposed methodology is presented in Sec. 3. Finally, Sec. 4 introduces the expert group report.

2. Overview

MOLecular COMunications (MolCom) has been a fruitful topic in the recent years and has attracted the interest of a broad research community. Up to now, the research interest in the field of MolCom has shown an exponential growth and we expect this trend to be maintained in the next few years. Fig. 1 (left) shows the historic of published papers per year in the field of MolCom. We show in light red the estimation for the next few years. Fig. 1 (right) shows the accumulated published papers by year, which approximates exponential growth.

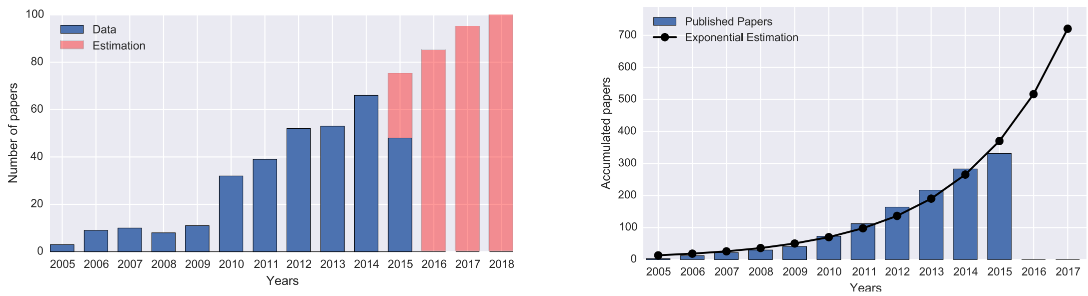

Figure 1. Historic of published papers per year

Unlike classical research fields, MolCom is defined as a highly multi-disciplinary area, which enables a plethora of applications in very diverse fields, being biology and medicine two of the most notable examples of future applications. In an effort to harmonize the disparate islands of knowledge in MolCom, identify the expert working groups and to derive specific roadmap, it is required to categorize the published research and to analyse the interrelation among fields of interest.

The relevance of a scientific research contribution is intimately dependent upon its relationship with current knowledge, the so-called State of the art. This is not just a list of references, but a structured classification of knowledge in the field.

In particular, the objective of a review of the State of the art is to become aware, knowledgeable and expert in a topic. This task is key to benchmark, highlight through evidence the uniqueness and novelty of the proposed contribution, to inspire future contributions and, finally, to establish roadmap.

In this report, we introduce a data science driven methodology to address the state of the art in an objective manner.

3. Methodology

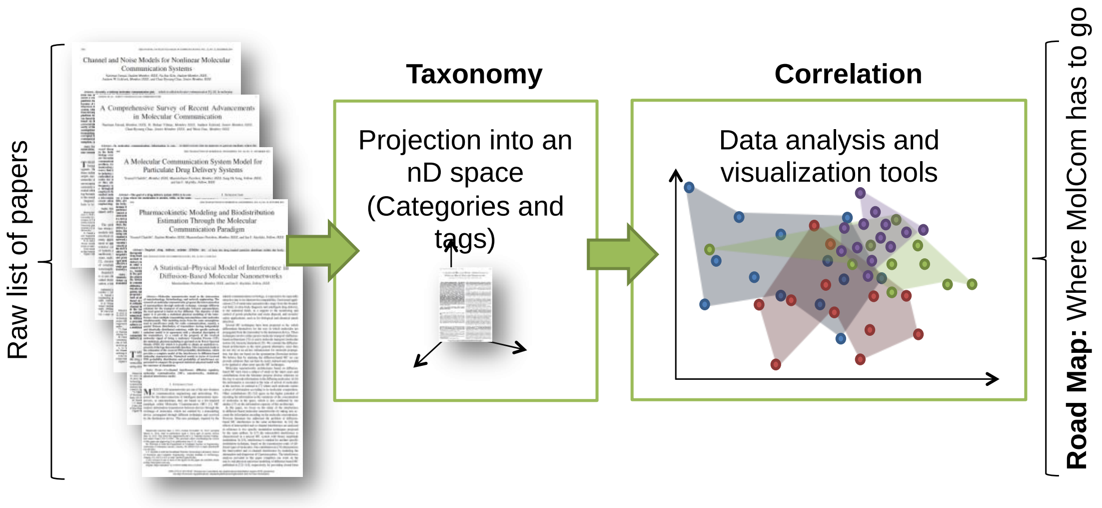

Figure 2. Proposed methodology work-flow

Reviewing the state of the art has traditionally been a time consuming task, targeted to cluster contributions as a function of different topics. This work introduces a data science approach, which aims at organizing the published research to date in an objective and time-efficient manner.

To achieve this vision, we have based this study on the collection of 360 papers, which are related to the Molecular Communication field. This set has been collected through data-base search and considers every paper presented, until March 21016, in the well-known reference manager *Mendeley* under the search criteria "molecular communications" plus additional papers, which have been published in *Elsevier NanoComNet* and *IEEE Transactions on Molecular, Biological and Multi-scale Communications*. An initial set of categories and tags are defined, such that each paper is projected against these. This step converts transforms a research paper into a quantitative magnitude, which can be processed with computer tools. After, the projected data is clustered as a function of the authors or institutions to help identify correlation among experts. It is expected that this analysis will provide a set of directions to establish the research roadmap. The work-flow is shown in Fig. 9.

The definition of a paper is done by assigning specific tags. These tags represent from a generic viewpoint the object of research and sub-disciplines of the paper, from the ICT perspective. To organize these, a set of categories are define, which cluster an undefined number of tags. Notice that tags are non-orthogonal. That is, a given paper can have more than one tag per category if necessary. Categories and tags are as follows:

Distance:

- Ultra-short range
- Short range
- Medium range
- Large range

Type of particles:

- Molecular Motors
- Hormones
- Neurotransmitters
- Diffusion
- Flow-based
- Walkway
- DNA
- Pheromones
- Bacteria
- Protein
- Calcium

Application:

- Neural
- Immune system
- Drug delivery
- Nature
- Tissue engineering
- Quorum sensing

Type of communication:

- Modulations
- Broadcast
- Unicast
- Multicast
- PHY-Layer
- Network architecture
- Channel
- MIMO
- Information Theory
- Architecture
- Coding
- Routing
- Multi-hop

Propagation dimensions

- 3D propagation
- 2D
- 1.5D
- 1D

Scope

- Theoretical
- Bio-chemical reality
- Generic/Survey
- Simulation

The projection of a given research paper over the disparate dimensions, which have been proposed, defines its profile. This is illustrated in the next figure (Fig. 3). As it is shown, dimensions are not quantitative. Instead, these are divided into multiple tags, being variable the number of possible tags at each dimension.

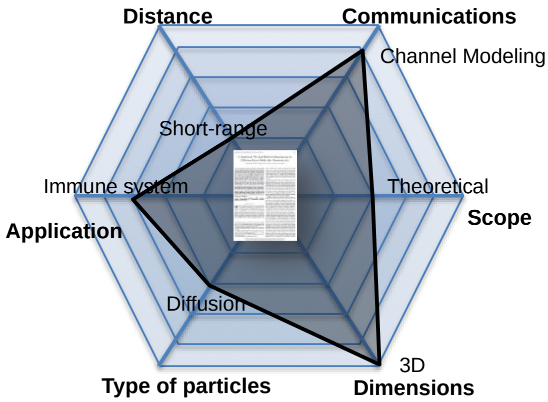

Figure 3. Example of a projected research paper over the proposed dimensions.

Profiles are not necessarily defined only for research papers, but these can also be defined for authors, institutions or sets of papers. We show the profile of the entire collection of papers according in Fig. 4.

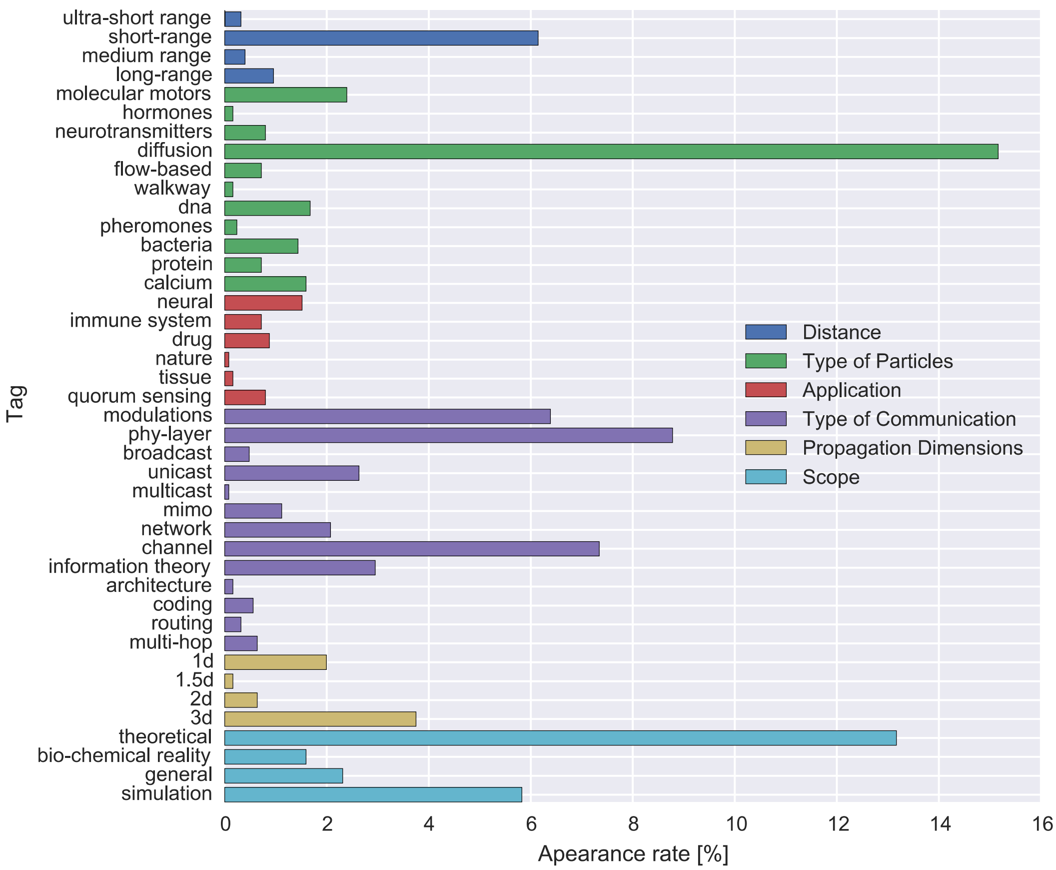

Figure 4. Profile of the entire collection of revised research papers in MolCom

We observe the following:

- Distance: Most of the research is carried out in the short-range.
- Type of particles: Diffusion-based molecular communication stands as the most active research field. Alternatively, molecular motors, DNA, bacteria and calcium signalling are also strong candidates.
- Type of communications: This category shows the largest diversity in terms of contributions. It is noticeable the large amount of work devoted to the physical layer, channel modelling and modulations.
- Propagation dimensions: Works are mostly divided into two large sets. First, 3D models which consider the particularities of the dispersive medium. Then, 1D environments, which capture a point-to-point link.
- Scope: Most works are theoretical, whit strong attention to simulation.

An additional database with all the appearing authors, affiliations and countries has been generated. A total of 420 authors belonging to XXX institutions have been found.

By connecting both databases we are able to quantify the problem and to identify the type of work that each author is working on. This generates a profile of each institution, which has been involved in the molecular communication research field. This aids finding potential collaborators, as well as we can identify potential authors that may be interested in a given field.

4. Expert Group Report

From the data analysis, we have obtained that a total of 375 authors, belonging to 131 different institutions worldwide have participated in, at least, the edition of one research paper. This includes the participation of researchers of neighboring disciplines, as well as young researchers, which have participated in a single paper. This fact is evidenced in Fig. 2, where 219 authors (58% of the total) have co-authored a single research paper.

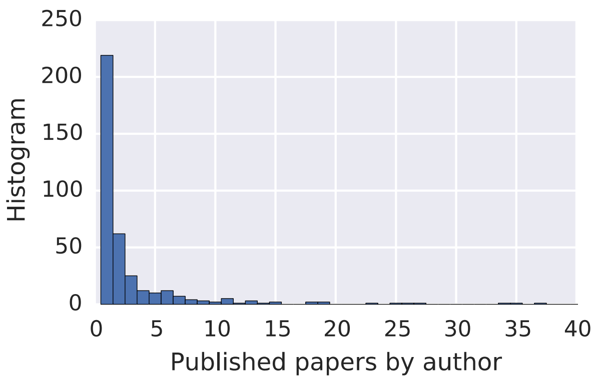

Figure 5. Histogram of the published papers by author.

4.1. Worldwide distribution of research

We list the times that a researcher belonging to a given continent has published a research paper in the field in Fig. 6. It is observed that 202 out of the 360 studied papers (56%) have been co-authored by an American researcher. This is followed by European institutions, which group 168 papers (45%).

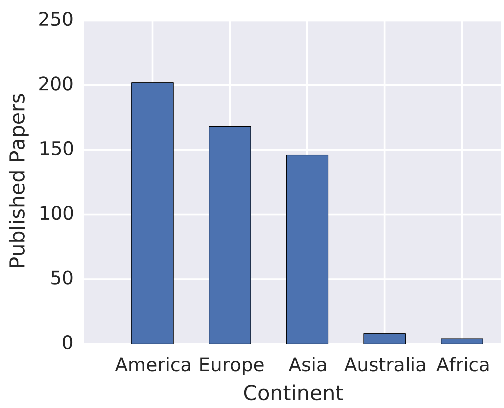

Figure 6. Number of published papers by continent

4.1.1. Cooperations between institutions:

Continent	Single institution or country-wide coop.	Single institution or continent-wide coop.	Total number of papers
America	68 (34%)	74 (37%)	202
Europe	63 (37%)	90 (54%)	168
Asia	31 (21%)	38 (26%)	146

Table 1. Cooperation between institutions and total number of papers per continents.

The large number of papers, which are co-authored by multiple research institutions, evidences the high multi-disciplinarity of the research field. This is shown in Table 1, where we account for the number of papers, which are either authored by authors of a single country, which have been authored by authors of the same continent. As it is shown, Asia is posed as the most cooperative continent, followed by America. In the particular case of European research, this is carried out, in its majority (54%) by only European institutions.

4.2. Top researchers

We select the most active research institutions, and the leading author from each, as the top researching institutions and authors in the field of MolCom. We consider that worldwide research is then influenced by them. This is shown, alphabetically sorted, in Table 2. Remarkably, two partners of CIRCLE belong this classification.

Researcher	Institution	Country
O. Akan	Koc University (Koc U)	Turkey
I. F. Akyildiz	Georgia Institute of Technology (GaTech)	USA
S. Balasubramaniam	Tampere University of Technology (TUT)	Finland
K.-C. Chen	National Taiwan University (NTU)	Taiwan
A. Eckford	York University (York U)	Canada
W. Guo	University of Warwick (Warwick)	UK
T. Nakano	Osaka University (Osaka U)	Japan

M. Pierobon	Univ. of Nebraska-Lincoln (UNL)	USA
T. Suda	Univ. Netgroup Inc. (Netgroup)	USA
T. Tugcu	Bogazici University (Bogazici U)	Turkey

Table 2. Top 10 researchers and institutions in MolCom (alphabetical order)

In addition, European research in MolCom is also influenced by the additional top+5 authors and institutions from Table 3, alphabetically sorted.

Author	*Institution*	*Country*
E. Alarcon	Universitat Politecnica de Catalunya (UPC)	Spain
F. Walsh	Waterford Institute of Technology (WIT)	Ireland
P. Lio'	University of Cambridge (Cambridge)	UK
G. Realli	University of Perugia (UNIPG)	Italy
R. Schober	Friedrich-Alexander-Universität (FAU)	Germany

Table 3. Top+5 European researchers and institutions in MolCom (alphabetical order)

The main research interests of each author and institution are as follows:

- O. Akan, Koc U.: Physical design of receiver based on nanoscale biosensors, network coding, channel model, mobile ad hoc, deterministic capacity, bio inspired network, molecular multiple access and error compensation and molecular communication method for energy transfer phenomenon.
- I. F. Akyildiz, GaTech: Physical layer and evaluation network metrics for diffusion and bacteria based molecular communications, targeting applications in the field of drug delivery.
- S. Balasubramaniam, TUT: Network protocol design for bacteria nanonetworks, calcium signaling, the Internet of NanoThings and bio-inspired adaptive networks, and cellular tissue modelling.
- A. Eckford, York U.: Application of information theory to molecular and biological systems. Including capacity analysis, brownian motion with drift and channel noise in diffusion-based molecular communication.
- W. Guo, Warwick: Channel model and physical layer techniques for molecular communication. Among others, pass-band modulations, ISI reduction and noise modelling.

- T. Nakano, Osaka U.: packet fragmentation, replication, retransmission, transmission rate control, propagation delay, channel model, capacity analysis, and repeater design in molecular communication.
- M. Pierobon, UNL: Drug delivery and diffusion-based molecular communication. Specifically, detection techniques, information capacity, noise analysis, channel memory, simulation of the physical layer and characterization of the diffusion channel.
- T. Suda, Netgroup: biological pattern formation (information molecules transmitted from a group of bio nano machines propagate and chemically react with the molecules in the environment forming an oscillating), molecular transport, microtubule topology, and gap junction.
- T. Tugcu, Bogacizi U.: Physical layer of diffusion based molecular communication: inter-symbol interference, modulation, channel capacity, routing and interference effect. He has also worked on calcium signaling.
- E. Alarcón, UPC: detection techniques, networking challenges and physical channel characterization of diffusion based molecular communications. Energy issues in nanoscale biological systems. Development of the N3Sim simulator framework.
- F. Walsh, WIT: Neuronal networks for molecular communications, virus nanonetworks and DNA based communications. Network protocols and addressing.
- P. Lio', Cambridge: Multi-scale multi-physics modeling of cell-tissue-organ interactions. Applications of molecular communications to medicine.
- G. Realli, UNIPG: Simulation driven analysis of molecular communication systems in blood vessels. Targeting drug delivery system applications. Development of the molecular simulator BiNS
- R. Schober, FAU: Mathematical model of ion channels and modulations, channel estimation techniques, communication protocols and nano transceiver design.

4.3. Relation among experts

The presented cooperation offers a tied network with multiple interrelations. In this context, the collaboration among experts is remarkable. We show in Fig. 9 the interconnection among major research groups. As it is observed, Europe is located at a strategic position in the research field, showing that most worldwide institutions have, at least, one European institution as solid partner.

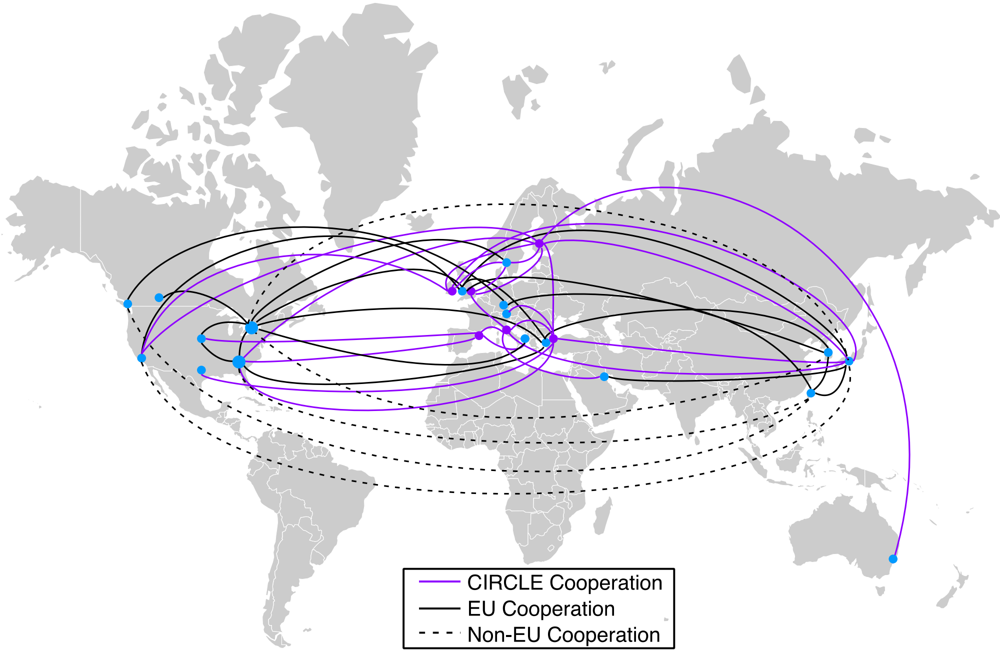

Figure 7. Existing cooperations among leading institutions in the field of MolCom.

In addition to this, the definition of research profiles at the institutional level, allows us to correlate the expertise of the different institutions. We, finally, highlight in Fig. 7 the orthogonality of each institution, as a metric to motivate future collaborations, if considering that experts in disparate disciplines are more likely to benefit from sharing knowledge and research outcomes. This is shown in Fig. 8.

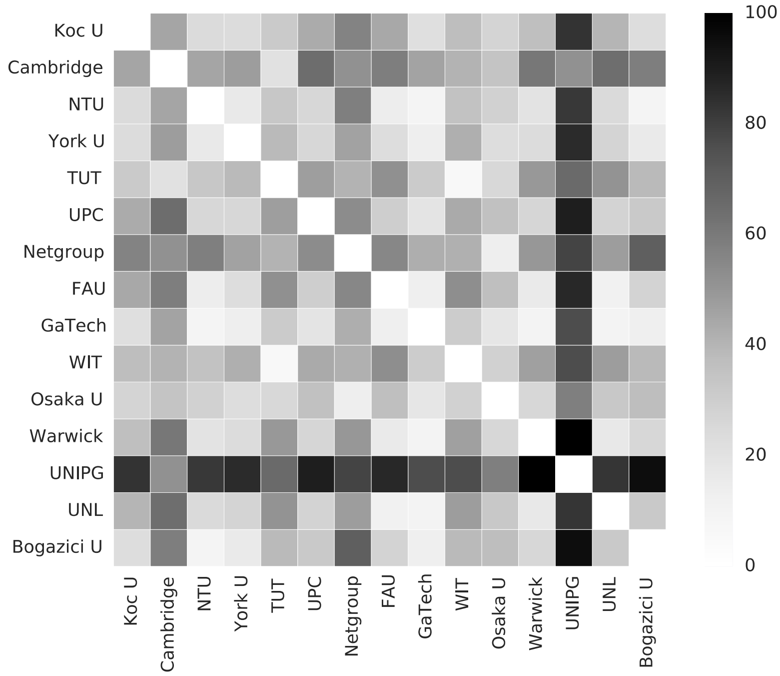

Figure 8. Research orthogonality among research institutions.