COntent Mediator architecture for content-aware nETworks

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Deliverable 7.4
Exploitation Plans and Future Deployment Roadmaps

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Table of Contents

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1 Executive Summary

Deliverable 7.4 briefly summarizes the achievements of the COMET project throughout its 3-year duration and presents both industrial and academic partners' exploitation measures and plans. This document answers the following main questions: **which** are the project's key assets that could be exploited**, why** are these results important, and finally, **by whom** and **when** they will be exploited.

Initially, a brief summary of the COMET project is provided, highlighting its major concepts, referencing work performed in work packages 1-6 and respective deliverables, including a brief description of the overall architecture, the two derived approaches (decoupled and coupled), their implemented prototypes and finally the federated testbed. Following this brief description, the project's exploitation foreground items list is given, divided into the following main categories:

- **Advancement of knowledge**, highlighting the key technical conclusions of the COMET project,
- **Algorithms and mechanisms**, introducing the novel mechanisms and algorithms of the coupled and decoupled approaches,
- **Models**, including the models and methods to study ICN-related approaches,
- **Simulators**, to study the feasibility of the designed mechanisms and algorithms,
- **Prototypes**, that implemented the designed COMET architecture and specified mechanisms,
- **Testbed**, where the implemented COMET prototypes were deployed and tested at a larger scale aiming to demonstrate the ICN concept.

A **SWOT analysis** is then performed, considering the project's strengths and weaknesses based on the simulation and performance tests and key research outcomes, the opportunities to exploit the project's results and finally, the identified threats, due to Internet market trends or currently deployed solutions and similar approaches. The performed analysis identifies certain aspects of the project's results, providing input to later sections of the document, where the consortium's exploitation strategy is explained. COMET partners will (a) exploit project's results, highlighting their strengths and advantages, (b) continue their research, aiming to improve the identified weaknesses and (c) seek to take advantage of the arising opportunities to strengthen the project's socioeconomic impact.

In addition, the consortium's **dissemination and standardization efforts** to promote the project's output in high-quality conferences, journals, workshops and standardization bodies are presented. Key information about published scientific papers is provided, as well as the project's main concertation, industrial dissemination and standardization measures, while the top five papers are highlighted based on their impact to the scientific community. These dissemination efforts reveal the quality of the work performed during the 3 years of the project, and will be the basis for the partners' exploitation measures and plans.

Finally, the consortium's exploitation strategy is briefly described, taking into account the derived list of exploitable foreground items, and the partners' **exploitation measures and plans**. More specifically, for each item, partners have specified their exploitation policy, providing certain information: its purpose, how the foreground could be exploited, when and by whom, further research necessary, and the expected socioeconomic impact. In general, the industrial partners of COMET will put effort in commercializing the implemented prototypes (ICN controlling and forwarding, server and network monitoring and routing awareness prototypes), aiming to either integrate them to their company's existing services and networks, or create new commercial products that could be added to their market portfolio. On the other hand, the project's results will be exploited by academic partners mainly through ongoing and future MScs, PhDs, courses and research projects. The consortium will also continue contributing to relevant standardization bodies, with great emphasis to the IETF IDF working group, aiming to BGP multi-path extension.

2 Introduction

Over the last few decades a significant evolution of the Internet usage model has been identified; it was originally based on a host-centric model, allowing hosts to interconnect for resource sharing purposes, while nowadays it is mainly used for a wide range of applications and services, and the majority of its traffic relates to content access and consumption. In addition, the continuing increase in user-generated content has created the need of an alternative approach to computer networks architecture, shifting from the traditional host-centric paradigm towards an information-centric one. In such an information-centric paradigm, a unified content naming scheme is introduced, content resolution and delivery functions are natively realized by the network in a location-independent fashion, and several content-centric mechanisms are adopted, such as in-network content caching.

Following this information-centric paradigm, during the 3 years of the COMET project, the consortium investigated, designed, simulated, implemented and tested mechanisms to make content access location-independent, supporting discovery, access, in-network caching and content/network-aware distribution for all types of content. It introduced a unified content naming, addressing and resolution architecture, where the user's request points to the content or service itself, rather than to the machine that hosts the content. In addition, server, network and routing awareness inherently improve QoS for content consumers, based on the content requirements.

This document is the last deliverable of WP7 and the project overall, briefly presenting key project outcomes and highlighting the consortium's efforts to disseminate, standardize and exploit the project's results. It identifies both industrial and academic partners' exploitation measures and plans, to increase the visibility and impact of COMET project and ICN paradigm in general, to the industrial sector, scientific community and society in general. Deliverable 7.4 is organized as follows:

Chapter 3 summarizes the key assets of the COMET project, its concept, the two derived approaches (coupled and decoupled) and their respective mechanisms and algorithms, the implemented prototypes and finally the federated testbed. Based on these results, this chapter presents and briefly describes which the project's exploitation foregrounds are.

In chapter 4, a SWOT analysis is performed, identifying the project's strengths and weaknesses based on the simulation and testing results, the opportunities to exploit these results and finally the threats that could possibly put barriers to COMET's deployment and adoption by Internet stakeholders.

The consortium's main dissemination, concertation and standardization activities are summarized in Chapter 5. It includes 3 tables, providing relevant information for (a) accepted scientific papers (including the five most important ones), and (b) all academic and industrial dissemination and standardization activities.

Chapter 6 gives a more detailed insight into the identified list of exploitable foreground items, providing the criteria for their selection, their type, and other relevant information, including their purpose, which partners, how and when they will exploit them, their socioeconomic impact and the required further research, addressing their weaknesses and aiming to strenthen their impact.

Finally, chapter 7 summarizes this document's main points and concludes the partners' exploitation measures and plans.

3 Overview of results

3.1 The COMET Concept

The basic concept of COMET was the design, implementation, testing and validation (both functional and non-functional) of a novel architecture model which acts as a mediator between Content Consumers and Content Servers. This mediation procedure relies on the user requesting content names, devoid of any information about the location and retrieval characteristics of the content, other than what the content is about, the architectural model being thus in charge of assigning an optimal content server and network path for content retrieval, according to user and content characteristics and requirements.

The COMET project fostered an architectural model composed of two planes: *A Mediation Plane (CMP)*, in charge of determining the optimal server and path for a content name request, and a *Content Forwarding Plane (CFP)*, in charge of transmitting the content through the path determined by the Mediation Plane, ensuring the QoS requirements associated to this content.

3.2 Accomplished Technical Work in COMET

During its three year life, work in COMET has followed the following stages, which have been reported in the different project deliverables:

- A general *architecture for Content and Network Mediation*, which can be realised following different approaches.
- A first adaptation of the COMET Architecture, the *Decoupled Approach*, aimed at general content distribution over the current Internet.
- A *Prototype of the Decoupled Approach*, envisaged as the basis for further deployment on an Internet Service Provider (ISP) network,
- A *COMET Federated testbed*, where the decoupled approach has been tested and evaluated, both functionally and non-functionally, i.e. in terms of performance.
- A second adaptation of the COMET Architecture, the *Coupled Approach*, which aims at distribution of popular contents over the current Internet.
- A Proof-of-Concept (*PoC) of the Coupled Approach,* to validate the concepts advanced in the Coupled Approach design.

3.2.1 Architecture for Content Mediation

In this architectural design, described in its final status in the deliverable D2.3 [3], the objective was the identification of the main functionalities which will populate the CMP and the CFP. In summary, the following functions were identified:

- The *Content Resolution Functional block (CRF)* of the CMP: It basically stores the mapping between Content Names and actual Contents Servers, as well content characteristics, in terms of QoS and retrieval.
- The *Path Management Functional block (PMF)* of the CMP: It stores information of routing paths connecting ISPs, as in BGP, but with information about long-term characteristics in terms of QoS.
- The *Server and Network Monitoring Functional block (SNMF)* of the CMP: It provides information about the status, in terms of availability of the contents servers distributing contents and network conditions.
- The *Content Mediation Functional block (CMF)* of the CMP: This function resolves content names into servers/paths, trying to find the optimal duple which ensures content retrieval with the appropriate QoS levels.
- The *Content-Aware Forwarding Functional block (CAFF)* of the CFP: CAFF are the functions which ensures proper packet transfer between the content server and the users

- The *Content-Aware Caching Functional block (CACF)* of the CFP: This function implements an in-network caching operation.

3.2.2 Decoupled Approach

The decoupled approach is one of the two adaptations of the architectural model advanced by COMET. The basic concept on which the decoupled approach relies is that resolution and forwarding are different processes as in the current Internet. Therefore, in the decoupled approach, the content names will be resolved first and once this operation is successful the network is configured for content transmission, effectively implementing a two step mechanism. Given its similarity to the current DNS-based operation in the current Internet, the decoupled approach can be regarded as an evolutionary paradigm towards the realisation of future content oriented Internet with QoS awareness.

Besides, in the decoupled approach each of the architectural functions described in section 3.2.1 is associated with a single entity. So there is a *Content Resolution Entity (CRE)* encapsulating the CRF, a *Routing Awareness Entity (RAE)* encapsulating the PMF, a *Server and Network Monitoring Entity (SNME),* encapsulating the SNMF, a *Content Mediation Entity (CME)*, encapsulating the CMF and a *Content-Aware Forwarding Entity (CAFE)* encapsulating the CAFF. The decoupled approach does not include the CACF within its architecture.

Complete specifications for the decoupled approach can be found at deliverables D3.2 [4] and D4.2 [6].

3.2.3 Decoupled Prototype

Based on the decoupled architectural design, a full prototype has been implemented and validated. The interfaces connecting the various entities in the decoupled approach have been fully specified as well as the mechanisms and algorithms ruling the operation of those entities. Each of these entities have been implemented using open source libraries based on standard programming languages (mainly Java, C++ and Python), ensuring its reusability and further adaptability. All the entities are designed to work both in IPv4 and IPv6.

The basic functionality of each entity, with stress on the interworking with related entities, was validated, so the prototype was functional and stable before starting its functional and non-functional experimentation and testing.

Description of the decoupled prototype can be found at D3.3 [5] and D4.3 [7], whereas validation is included in D5.1 [8].

3.2.4 COMET Federated Testbed

To carry out the functional and non-functional (i.e. performance) validation of the decoupled prototype, a federated COMET testbed has been set up, connecting three isolated testbeds in partners' premises (namely, Primetel, TID and WUT), where the decoupled software prototype was deployed. This federated testbed simulates five ISPs, allowing multiple combinations of content servers and routing, which make the testbed's conditions close to those of the real Internet.

Over this testbed, two of the envisaged use cases defined in D2.2 [2] were tested and tried, demonstrating that the COMET system is not only functional, but specially aligned with the interests of content providers, which who, by using a single content name, can maintain a diverse population of content servers (Streaming, VoD, P2P). The composition of this server population can vary in time, according to users' and providers' need, without the end users being aware of the changes and the users being transparently redirected to the serves best fitting their profiles.

The COMET Federated Testbed and the evaluation activities performed over it are described in D6.2 [11].

3.2.5 Coupled Approach

In the coupled approach realisation, on the contrary, there is no separation between content resolution and content forwarding which will be carried out in parallel to implement a one-step mechanism. In other words, a successful content resolution is signalled by the reception of the content, without requiring a second content request as in the decoupled. Also central to the coupled approach is that routing and resolution is handled on a domain-level on a hop-by-hop basis, with each coupled entity being only aware of those in neighbouring domains, effectively distributing processing load across the network. Such a scheme represents a more radical approach as alternative pathway leading towards future content/information centric Internet and technically it is deemed as a promising paradigm for handling extremely popular content in the Internet through graceful support of inter-domain content multicasting.

Hence, the function mapping to entities is different to the decoupled approach. The CMF, CRF and SNMF are encapsulated in a single entity, the *Content Resolution and Mediation Entity* (CRMF), while the PMF and the CAFF are respectively encapsulated in the *Routing Awareness Entity (RAE)* and *Content-Aware Forwarding Entity (CAFE)*. CAFEs also contain the CACF function as sketched in the overall architecture model.

Complete specifications for the coupled approach can be found at deliverables D3.2 [4] and D4.2 [6].

3.2.6 Coupled PoC

A proof-of-concept emulator has been developed to validate the concepts of the coupled approach. Specifically, this emulator implements a number of key functionalities of the coupled approach, such as content publication, content resolution, and content delivery (including the ability to optimise the content delivery path along available peering links). A basic content caching mechanism has also been implemented to demonstrate the ability of the coupled approach to reduce the need for content requests to be sent all the way to the server hosting the requested content.

The emulator has been built on top of the Very Lightweight Network and Service Platform (VLNSP) [24], which is a Java-based platform containing a lightweight implementation of IP. To demonstrate the concepts visually, a graphical hook-in interface has been developed using Graphviz [25]. This interface shows the main COMET components (CRME, CAFE, Content Client, and Content Server, as well as the messages that they exchange.

A description of the coupled PoC can be found in D3.3 [5] and D4.3 [7], whereas validation is included in D5.1 [8].

3.3 Exploitable Foregrounds obtained from the accomplished work

In the context of the work briefly sketched above, the consortium has been able to produce the following foregrounds which will be exploited after the end of the project. A more detailed description as well as the justification for their selection is included in section 6.

3.3.1 Advancement of knowledge

3.3.1.1 ICN feasibility at internet-scale

One of the main requirements for ICN systems is its feasibility for deployment at internet-scale networks. The analyses, simulation experiments and trials performed in the COMET federated testbed confirmed that both COMET approaches, i.e. the decoupled and the coupled, are feasible for deployment at internet-scale. They are **complementary** in the sense that the coupled approach, with graceful support of in-network caching, is more suitable for the delivery of **highly popular** content, while the decoupled approach is more suitable for delivering other types of content objects which account for the **majority of the content items in the Internet**. The main conclusions about deployment feasibility are the following:

For the decoupled approach: The performed experiments confirmed that there is no critical element in the COMET decoupled system, which could lead to the performance degradation in case of system deployment at internet-scale. The content resolution process performed even under highly loaded COMET entities assures that the content resolution delays are on the level satisfying customers(less that 2.5 s for 95 percentile of content requests). This feature derives from the fact that the content resolution process is mainly performed at network edges, i.e. at the client and server domains. So, if we have problems with handing large number of content requests in a given domain, the operator can offload the COMET entities by adding new mediation instances in this domain. From the point of view of content delivery, the stateless packet forwarding mechanism allows to keep small routing tables in network nodes as it stores only local information. On the other hand, the size of additional header inserted to packets is less or equal to 8 bytes for the 99% of routing paths available in the current Internet.

For the coupled approach: The use of broadcast resolution is able to improve the content resolution performance compared to the random resolution option. However this is at the expense of higher complexity and communication overhead between neighbouring domains. There are various factors that may have impact on the difference between the two options, in particular the popularity of domain-level multi-homing. The resulting content delivery path after the initial content resolution can be long due to the unknown location of the content source. The proposed mechanism for post-resolution path optimisation is able to achieve enhanced results which can be as good as that is based on conventional BGP routing in which case the location of the content source is known a priori. In addition, our studies have shown that the domain-level hop count does not vary considerably with topology size, making the coupled approach a purely feasible option from a scalability perspective, and hence resulting in worst-case content retrievals of well under one second. This observation is consistent with the “small-world” feature of the Internet topology that has been reported in the literature.

More details related to feasibility studies are reported in D5.2 [9].

3.3.1.2 "Cache less for more" recommendation

The “cache less for more” paradigm advocates against the necessity of ubiquitous caching, that is, against caching all contents in all caching nodes in a network or path of caches. We have observed that caching all requested content objects in all caching nodes leads to redundancy between different caches and therefore, in inefficient use of existing cache resources. Although similar observations have been made in the past for hierarchical and web-caching systems, the impact of ubiquitous caching in in-network caching systems had not been investigated before. Under the “cache less for more” paradigm contents are cached in selected nodes in the network to reduce caching redundancy.

As we detail later on in this section, the COMET project has produced two different approaches to in-network caching, namely one based on the centrality of nodes [13] and a second one based on the cache capacity of on-path caches from source to destination [12].

3.3.2 Algorithms and mechanisms

3.3.2.1 Gossip-based content resolution mechanism

As discussed in detail in earlier deliverables, content resolution in ICN environments differs hugely from traditional host-to-host communications. That is, the resolution mode has to search for content explicitly, instead of searching for the machine that hosts the requested content. The gossip-based content resolution is a mechanism that searches for content in a hop-by-hop fashion in individual domains. The mechanism includes all required stages of a content’s lifetime, from content publication, to content resolution and delivery. After a content is published, the resolution mode is forwarding requests in a hop-by-hop fashion along domains, based on the position of each hop in the hierarchy, as well as based on the business relationships between neighbouring domains.

Further details regarding the specifics of the gossip-based content resolution, which has been instantiated in the CURLING approach, can be found in [19][20].

3.3.2.2 Multi-criteria server and path selection algorithm

One of the fundamental problems in ICN systems is a proper selection of the content server streaming the content requested by a consumer. By using information about the servers' load and network conditions, the ICN system gains in effectiveness, which is reflected in better quality of experienced by users (QoE), improved system resources utilisation and improved the load-balancing within the network and between servers. Nevertheless, the selection process is a complex multi-criteria optimization problem.

The proposed multi-criteria server and path selection algorithm takes candidate duples of server/path and orders them according to a ranking, so the candidate duples with the higher values in the ranking are preferred for content delivery. In order to estimate the ranking, the algorithm creates a decision space based on vectors of decision variables related to the load server, the packet transfer delay, packet loss and available bandwidth in the path, as well as the distance between server and consumer expressed by the number of hops in the path. These decision variables are parameterised according to two factors, the reservation level and the aspiration level. The reservation level is the hard upper limit for the decision variable which should not be crossed by the preferred duple. On the other hand, the aspiration level defines the lower bound for decision variable, beyond which preference is similar. The ICN operator may tune the behaviour of the decision algorithm and enforce own policies by setting reservation and aspiration levels.

More details for this algorithm and performance evaluation results can be found in D3.2 [4], D5.2 [9] as well as in [26] and [27].

3.3.2.3 Multi-path and multi-criteria routing algorithm

The current Internet relays on shortest path routing paradigm with a single routing path established between any two domains. This approach limits the effectiveness of content delivery because (1) the network transfers the content regardless of its QoS requirements, which generally leads to degradation of the quality experienced by consumers, and (2) downloading of popular content may provoke network congestion, since routing creates only a single path going from content server to customer domains.

The designed multi-path and multi-criteria routing algorithm overcomes the above limitations and creates a number of content delivery paths between server and consumer domains with respect to content QoS requirements. The algorithm follows the path vector principle, where routing entities advertise to their neighbours a set of preferred paths. Each path is characterised by a list of domains (AS numbers) and the corresponding vector of path weights calculated as concatenation of links weights. Such path characteristics allow the routing entity to eliminate routing loops, remove unfeasible and dominated paths and rank paths based on domain policies. The designed algorithm ranks paths based on Minkowski norm of order r, which prefers paths with larger distance from constraints. Each routing entity advertises to its neighbours a number of preferred paths, which finally results in a number of end-t-end paths calculated between any pair of domains.

Full details for this algorithm and performance evaluation results can be found in D4.2 [6], D5.2 [9] as well as in [26].

3.3.2.4 Stateless packet forwarding mechanism

The stateless packet forwarding follows the source routing principle at the domain level. The idea of the stateless packet forwarding mechanism lies on configuring the network elements at the beginning of a data flow (for instance the data sent by a content server to a client) with a list of forwarding keys which identifies the network interface each successive element in the path have to relay the packets it receives.

The stateless packet forwarding assumes that nodes maintain only the neighborhood (local) information, i.e., how to forward packet to the peering nodes. All information about routing path is stored in a header attached to the original packet. The header includes information of the end-to-end path expressed by a list of forwarding keys, which allows nodes to forward packets to the next node in the selected path. The header is attached and removed by the edge node located close to the content server and the client, respectively. We assume that the end-to-end path is selected and configured in the edge node at the server side during the call setup before the forwarding process.

The proposed approach allows: (1) flexible selection of routing path for each data flow enabling new traffic engineering algorithms, (2) applying specific packet processing mechanisms within nodes, which support mobility, flow redirection, multicast, QoS, security, etc., (3) use different packet forwarding technologies between peering CAFEs.

More details for this algorithm and results of performance evaluation are reported in D4.2 [6], D5.2 [9], and D6.2 [11].

3.3.2.5 In-network caching mechanisms

As discussed before, we have observed and shown (through simulations) that caching all contents in all caching nodes in the network or path, results in inefficient cache resource utilisation. Therefore, we have developed two in-network caching approaches that selectively choose and cache contents in limited places in the network. The first mechanism is based on the centrality of nodes in a domain. In particular, contents are cached in the highest centrality node along the delivery path. The detailed description of this mechanism can be found in [13]. The second approach developed in COMET is a probabilistic caching algorithm, which approximates the cache capacity along the delivery path and caches contents according to a probability function. The purpose is to guarantee that all flows get equal opportunities to exploit the in-network caches depending on the length of the path they are traversing from source to destination. The details of the probabilistic caching algorithm called *ProbCache* can be found in [12].

3.3.3 Models

3.3.3.1 In-network caching models

Adding cache memory to routers in the network potentially changes the dynamics of the traffic flow. In COMET we identified the need for such new models to describe the behaviour of these new cache elements. We have therefore, built a model that approximates the proportion of time that a given content stays in the cache, or in other words the probability that a content request will result in a cache hit [14]. Our model requires a fixed and known network topology and related requests rates for the contents in the network. It is based on continuous time Markov Chains. Although our initial model applies to ubiquitous caching strategies, where contents are cached to every cache they traverse, we have extended our model to apply to a wide variety of caching strategies, such as the probabilistic caching approach discussed above.

3.3.3.2 ICN evaluation method

Most of ICN systems are designed for deployment at internet-scale networks. The evaluation requires development of simulation/analytical models of ICN system processes and definition of large scale model of video content system.

In COMET, we identified that the content resolution process is the most critical from the point of view of system performance and scalability. We model the content resolution process as an open queuing network, where particular COMET entities play the role of servers. The queuing network is fed by the arrivals of content requests. Each request initiates the sequence of tasks executed in different servers. The input data for our models, corresponding to execution times of the tasks performed in particular COMET entities, were obtained from the experiments carried out on the COMET prototype deployed over the federated testbed, as reported in D6.1 [10] and D6.2 [11].The COMET evaluation was performed based on defined large-scale network model for ICN system evaluation. This model takes into account: (1) a large-scale model of Internet topology, (2) content server location and characteristics, and (3) content characteristics and distribution. The model of Internet topology is based on AS-level data sets provided by the Cooperative Association for Internet Data Analysis (CAIDA) and covers 36,878 domains, where approximately half of them are stub domains, and 206,969 inter-domain links. The content server location and characteristics are defined based on the analysis of the 50 largest video content providers and Content Distribution Networks (CDNs). The characteristics of the video content and its distribution are based on analysis of 5,000 most popular titles.

In our studies, we evaluated what is the impact of increased system size (request rate, number of content sources, domain size and number of domains) on the content resolution and content delivery processes.

The details of ICN evaluation method, defined simulation/analytical models and obtained results are presented in D5.2 [9].

3.3.4 ICN Simulators

Apart from theoretical modelling, the behaviour of a network can also be evaluated by simulation experiments. The specific characteristics of in-network caching environments have been integrated in a python-based simulator, which we have built for the purpose of evaluating the behaviour of our proposed in-network caching strategies (e.g., [12], [13]). The simulator includes the implementation of proposals from other researchers in the area, and we are currently in the process of integrating even more caching strategies [15]. In addition, a Matlab-based simulator was built for the performance evaluation of the CURLING paradigm within large-scale topologies, and 3 more simulators for performance evaluation of (1) multi-criteria decision, (2) multi-path and multi-criteria routing algorithms and (3) content resolution procedure.

3.3.5 Prototypes

3.3.5.1 ICN controller and forwarding prototype

The ICN controller and forwarding prototype has a twofold functionality. On one side it will determine which path is optimal in terms of QoS for distributing a particular content, using the aforementioned multi-path and multi-criteria routing algorithm, which could be fed with the information obtained for the Routing Awareness prototype (see below).

The selected path, expressed in AS list format, can then be translated into a key list format as defined in the stateless packet forwarding mechanism so that forwarding elements can be configured with this information, enabling them to capture the packets with a defined origin and relay them, forwarding element after forwarding element, after they reach their expected destination, ensuring a required QoS level along the entire path.

The controller prototype will monitor how many flows and with which requirements are active in the forwarding prototypes under its direct influence, so it can decide when they are no longer in use and when new flow requests cannot be served with the resources at its disposal.

Full details for this prototype can be found at D3.2 [4] and D4.2 [6].

3.3.5.2 Server and network monitoring prototype

This element collects and consolidates real-time status information about content servers in three predefined status (high, normal, low), so that any external entity could query about server status and receive updated information about the health of the content server, which can use in its internal algorithms.

The core of the server and network monitoring prototype lies on the deployment on light pieces of SW on the content servers, which will continually monitor several status parameters (CPU load, memory occupation, and bandwidth usage) which will be fed into a threefold decision algorithm with will estimate the predefined status (high, normal and low) using not only the measure fed but the previous one. The evaluated status is sent periodically to the server and network monitoring prototype where it can be stored and updated for further use.

Full details for this prototype can be found at D3.2 [4].

3.3.5.3 Routing awareness prototype

The concept behind the routing awareness prototype is an element which can be configured with local routing information, inside the area it manages and to the neighbouring areas, typically ISPs. By the exchanging Network Layer Reachability Information (NLRI) records among a peering Routing Awareness Entities, the routes from one ISP to another can be calculated by each Routing Awareness Entity, so external entities can use this information to route packets from one ISP to another.

The difference of the routing awareness prototype with BGP routers lies on the fact that this prototype exploits the described multi-path and multi-criteria routing algorithm instead of the single, shortest path routing algorithm. As a consequence, the routing awareness prototype provides a number of alternative paths between any source and destination domain. Moreover, these paths are calculated using information about packet loss/packet delay/bandwidth as provisioned in the propagated routes, so an external entity can use this information to decide which routes should be used in order to ensure QoS for a given service, e.g. a content distribution service.

More details about this prototype and performance results can be found in D3.3 [5] and D6.2 [11].

3.3.6 ICN Testbed

The COMET project designed and deployed the ICN federated testbed aimed to validate the COMET's decoupled approach in the environment which is as close to a real system as possible. The federated ICN testbed consists of three local testbeds located at partner premises, Madrid/TID, Limassol/PTL and Warsaw/WUT, which are connected by OpenVPN tunnels established over the Internet. The testbed emulates five ISPs, where four of them host consumers and content servers, while one ISP is the transit ISP. The topology is set up in such a way to allow for a content client to request content from any content server at remote ISPs, while involving at least one intermediate ISP. Moreover multiple network paths and multiple content servers are set up to allow for all necessary selection options in terms of server load, path characteristics and quality of service. The federated ICN testbed allows performing experiments focused on ICN functionalities as well as the performance of the COMET prototype.

More details about federated ICN testbed can be found in D6.2 [11].

4 SWOT analysis of results

4.1 Strengths

Possible Strengths	Response
Is the COMET architecture unique or market leading?	The proposed approaches in COMET provide two novel and nicely complementary solutions for ICN provisioning which offer content name based resolution and forwarding as compared to the current internet (See also Sections 3.2.2 and 3.2.5). Due to the market growth in CDNs, stakeholders including Network Operators and Content Providers are interested in new developments and advances in novel content delivery [31].
Can the COMET individual components be used independently?	Some of the COMET components are used for independent functionalities, like routing, content registration, content resolution, caching mechanisms etc. and can be reused independently. These include CAFEs, RAEs, CREs. Novel mechanisms and algorithms can also be further exploited in other ICN architectures.
Does the COMET approach have any cost advantages over existing approaches?	COMET has proved that it can easily be further developed to incorporate costs when it comes to Content Server and Path selection. This was illustrated in the COMET-ENVISION integrated scenario which was demonstrated and described in [11].
Does COMET yield sufficiently good performance in supporting content access and delivery?	The decoupled approached was tested for functionality and performance in WP6. Performance gains are described in [11]. Through the validation phase it was proven that COMET can perform better than the set thresholds and performance metrics. Functional testing illustrated that the novel approach is fully operational.
Can the COMET approach scale to a global level?	At the validation stage together with scalability analysis in WP5 it was illustrated that the decoupled approach could scale to a global level. This also applies to the coupled approach. However it should be noted that the coupled approach is not supposed to support all the content items, but only highly popular ones which accounts for a small proportion of the Internet content items.
Is the standardisation Community aware of the COMET approach?	ICN issues related to COMET have been discussed in ICNRG of IRTF and CDNi WG of IETF. COMET has also contributed to relevant Internet drafts.
Has COMET been promoted effectively?	COMET has been promoted effectively through prestigious conferences, journals and magazines including IEEE Communications Magazine, Elsevier Computer Communications, CRC Press, Taylor & Francis, as well as well popular conferences like IFIP Networking, IEEE/IFIP NOMS, IEEE ICC/Globecom, specialised workshops under the top-tier conferences like ACM SIGCOMM, CoNext and IEEE LCN, as well as EU concertation events, such as FIA plenary meetings, and the NEM Summit.
Are there potential customers?	NSPs and Content Providers are potential customers of this technology for better provisioning of their content services.
Is it easy to deploy the architecture?	It has been demonstrated in WP6 that the decoupled approach could be easily deployed on the current operator infrastructures as well as across multiple operators.

Has the COMET approach been advertised effectively?	Besides being promoted through conferences, books, journals, magazines, workshops, COMET has also been promoted through company's magazines both nationally and internationally (online) e.g. Primetime Magazine.
Is the approach novel/innovative?	COMET proposed two ICN approaches with novelties in content resolution and forwarding (More information in section 3.2.). The results have been accepted for publication in several tier-1 publications.

4.2 Weaknesses

Possible Weaknesses	Response
Is the deployment strategy too ambitious?	Between the two approaches the decoupled approach has been demonstrated and validated effectively as easily deployed over current infrastructures. The coupled approach is more ambitious because of placing content access and delivery at centre stage. This is a common case for other radical approaches that have been proposed in the literature such as NDN/DONA and other schemes
Is the migration strategy from existing technology easy?	Migration towards the decoupled could be achievable in the short term by being deployed over the current Internet. The coupled approach is more futuristic, with content-centric access and addressing and will mean a big step from the existing host-centric internet.
Are the components too expensive to be deployed worldwide? Do you predict high overall component costs compared to the competition?	The components are in prototype phase hence no real costs could be predicted. A cost or techno-economical analysis has not been achieved in the project.
Have you faced problems in that the approach could not scale or bottlenecks were identified?	It was demonstrated in the simulation and validation testing that the decoupled approach could scale. Certain faced bottlenecks need to be corrected in the component implementation to accept requests from a really large pool of clients. This was caused by requests been received at more or less the same time causing components to react below the expected threshold. Concerning the coupled approach, it's not our intention to make it scale to support all content objects in the Internet, but only highly popular items.
No large-scale prototype for the coupled approach	A proof-of-concept emulator was created to implement and validate the coupled approach's mechanisms and functionalities. However, a full prototype could have been implemented, to be deployed in the federated testbed and further tested in a larger scale.
Both approaches were simulated, but not deployed in large-scale scenario	The COMET consortium has designed and created the federated testbed to validate and test the developed prototype. In addition, the scalability and feasibility of both approaches to current Internet was proved through simulations. However, due to limited resources, both approaches were not deployed in a large-scale, real-world scenario, which could identify certain weaknesses of the prototype and provide results of approaches' performance.
Do the partners involved own any patents or proprietary technology?	No patents where filed for the prototyping developments which however were kept disclosed under the consortium agreement.

4.3 Opportunities

Possible Opportunities	Response
Can the COMET approach be further optimised?	The COMET approaches proposed within the project duration already went through a number of software revisions. Further revisions are possible and could be based on the outcomes of the validation tests.
Can the current internet migrate to the COMET approach for content provisioning and retrieval?	The decoupled approach could easily be added as an overlay without requiring modifications to how the internet works. The coupled approach is more revolutionary and requires a long term plan for migrating towards an ICN paradigm.
Can the customer base be easily expanded?	It was validated that a large number of contents and a large number of customers could be served and only limited by the hardware resources used.
Will the COMET approach create new market opportunities?	The COMET approach will provide new market opportunities to Network Service Providers as well as Content Providers.
Can the COMET approach encourage healthy antagonism between involved stakeholders?	COMET provides ICN approaches which evolve around content name resolution and forwarding. This brings alternative solutions to CDNs which can be offered by network service providers and can encourage antagonism with CDN providers.
Could COMET help to improve multimedia content delivery?	COMET proposes an ICN approach for all registration, addressing, resolution, requesting and delivery of content which supports multimedia content delivery and improves selection in server and path selection.
Will COMET provide new opportunities for CDN providers?	COMET approaches could be exploited both by NSPs as well as CDN providers. The COMET system is more content name centric making it clearer to both providers as well as customers which will promote improved awareness of a contents providers services.
Will COMET benefit from recently established research initiatives like IRTF ICNRG?	The IRTF ICNRG was recently chartered and held its first interim meeting, where COMET and other ICN approaches have presented their concepts and discussed the potential of ICN deployment to the Internet. On the one hand, ICNRG offers an idea channel for the COMET project to efficiently disseminate our research outputs during and even after the lifetime of the project. Meanwhile, COMET could also benefit from the RG's discussions and work, to identify certain improvements to its mechanisms, as well business opportunities and incentives to increase its potential for deployment.

4.4 Threats

Possible Threats	Response
Will advances in CDNs be preferred over COMET's ICN approaches?	In the short term the benefits of ICN may not be so clear and advances in CDN may not allow for a more intrinsic solution to be updated across the internet due to lack of awareness. However, even if the CDN pathway is preferred, the proposed COMET approach is still able to gracefully co-exist with CDN infrastructures with seamless interoperation.
Do stakeholders or consumers have a choice for using alternative methods for Content delivery?	CDN will be the obvious alternative approach which is currently used.
Unclear incentive for stakeholders to deploy COMET solution	Nowadays, NSPs are paid by CDN providers to host their edge servers, and also by lower-tier ISPs for backbone traffic. Through the adoption of COMET, they would lose part of their revenue from CDN providers, but gain from their collaboration with CSPs. Hence, at this point their incentive seems rather unclear, and further study is required.
Competition with other ICN solutions and existing content delivery platforms	COMET is among multiple ICN solutions and architectures, investigating ways to improve content access and delivery. EU-funded projects, e.g. PURSUIT, SAIL, and US-based projects, such as CCN, CCN/NDN, constitute significant competition for COMET in the ICN area. In addition, nowadays content distribution and delivery relies heavily on CDNs and clouds. Hence, COMET should improve its weaknesses and further expand its features to compete with all the aforementioned solutions.
Legal issues	COMET has designed and implemented a unified content publication and access platform, in which content owners and providers are able to distribute their content. A global naming scheme was also introduced to identify content providers and items. However, COMET has not investigated intellectual rights' cases, which could be a potential threat for its deployment potential and adoption by NSPs and CPs.

5 Dissemination measures

During the three years of the project, the COMET consortium has disseminated the aforementioned project's results to high-quality concertation, academic and industrial dissemination and standardization events. Table 5-1 presents the list of scientific papers, firstly introducing the 5 most important ones, while Table 5-2 includes all partners' dissemination activities.

The project's top five papers were selected based on the combination of the following criteria: (1) the number of citations[1], (2) the tier of the conference / journal[2] and (3) their scientific impact[3]. The COMET consortium has identified the following papers as the ones highlighting the COMET project:

- **Modelling and Evaluation of CCN Caching Trees** – This paper is one of the first works in the literature on analytical modelling of the internationally well-known CCN/NDN approach using continuous time Markov Chain. It is published in the internationally well-established IFIP NETWORKING conference which consistently maintains an acceptance rate of about 25%. It has now been cited as one of the main resource on understanding the CCN and in a more general context, ICN. Its citation is still increasing. The extension of this work has been submitted to the Elsevier Computer Networks, Special Issue on Information-centric Networks.
- **CURLING: Content-Ubiquitous Resolution and Delivery Infrastructure For Next Generation Services** – This paper representing COMET's coupled approach, published at the IEEE Communications Magazine with impact factor of 3.785, is now one of the main recognised ICN architectures in the literature and regularly recording new citations especially by work related to architecture design for ICN and content networks in general. In addition to that, the IRTF ICN RG has also recognized the proposed receiver-driven hop-by-hop hierarchical content resolution as another potential future content dissemination approach.
- **Probabilistic In-Network Caching for Information-Centric Networks** – This paper is published in one of the two main ICN workshops. It is co-located under the ACM SIGCOMM conference and a very selective workshop (acceptance rate: ~23.9%). The work is constantly getting new citations. The extension of this work has been submitted to the IEEE Transactions on Parallel and Distributed Systems (Impact factor 1.4) and is currently under revision.
- **Cache "Less for More" in Information-centric Networks** – This paper, arguing against the conventional indiscriminate caching and showing that even simple random selective caching can provide better gain, has received accolades internationally. It has been recognized by the International Federation of Information Processing (IFIP) and awarded the Best Paper Award in IFIP NETWORKING 2012. The award committee has commended that the paper's contribution reach farther than ICN area and its conclusions are applicable to the general area of caching. It has also recently been included as baseline input to the IRTF ICN RG. Like the above papers, it is currently getting new citations regularly. Its extended version has just been published in the Elsevier Computer Communications Journal (Impact factor 1.2), Special Issue on Information-Centric Networking where the

[1]The citations are based on the record from Google Scholar.

[2]Tier 1 conferences are defined as those with an acceptance rate of 30% or lower in the widely regarded Networking Conferences Statistics maintained by Kevin Almeroth at the University of California, Santa Barbara (see: http://www.cs.ucsb.edu/~almeroth/conf/stats/) while tier 2 conferences are defined as these with an acceptance rate of 40% or lower in the same set of statistics. We define IEEE journals as being tier 1 publications, while tier 2 includes well reputed periodicals, such as those published by ACM, Elsevier or Springer.

[3]Wherever possible, the latest published impact factor of the relevant journal is also taken into account.

guest editors are composed of main CCN/ICN experts (BengtAhlgren, Holger Karl, Dirk Kutscher, Lixia Zhang).

- **Multi-criteria decision algorithms for efficient content delivery in information-centric networks** – This paper deals with the more general problem of content delivery over the Internet (e.g., in content delivery networks (CDNs), information-centric networks etc.) and is most relevant to COMET's decoupled approach. The reviewers have highlighted the wide applicability of the proposed algorithms. It has just been published recently with Springer's open access (providing free public access) and it is expected to make an impact in the research area of content delivery.

Table 5-1: List of scientific publications

LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE 5 MOST IMPORTANT ONES											
No.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers	Tier	Number of citations
1	**Modelling and Evaluation of CCN Caching Trees**	**UCL**	**Proceedings of the 10th international IFIP Conference on Networking**	**10/05/2011**	**IFIP**	**Valencia, Spain**	**2011**	**78-91**	**DOI: 10.1007/978-3-642-20757-0_7**	**1**	**42**
2	**CURLING: Content-Ubiquitous Resolution and Delivery Infrastructure For Next Generation Services**	**UNIS**	**IEEE Communications Magazine, Special Issue on "Future Media Internet"**	**Vol. 49, no. 3**	**IEEE**	**N/A**	**2011**	**112-120**	**DOI: 10.1109/MCOM.2011.5723808**	**1**	**37**
3	**Probabilistic In-Network Caching for Information-Centric Networks**	**UCL**	**ACM SIGCOMM Workshop on Information-Centric Networks**	**17/08/2012**	**ACM**	**Helsinki, Finland,**	**2012**	**55-60**	**DOI: 10.1145/2342488.2342501**	**1**[4]	**14**
4	**Cache "Less for More" in Information-centric Networks**	**UCL**	**11th International IFIP Conference on Networking**	**21-25/05/2012**	**IFIP**	**Prague, Czech Republic,**	**2012**	**27-40**	**DOI: 10.1007/978-3-642-30045-5_3**	**1**	**12**
5	**Multi-criteria decision algorithms for efficient content delivery in information-centric networks**	**WUT**	**Annals of Telecommunications, special issue on Networked Digital Media**	**Vol. 68, no. 3-4**	**Springer**	**N/A**	**2013**	**153-165**	**DOI: 10.1007/s12243-012-0321-z**	**2**	**3**
6	A Dynamic Peer-to-Peer Traffic Limiting Policy for ISP Networks	UNIS	Network Operations and Management Symposium (NOMS'2010)	19/04/2010	IEEE/IFIP	Osaka, Japan	2010	317 - 324	DOI: 10.1109/NOMS.2010.5488483	1	3

[4] The ACM workshop is in principle not tiered, however considering that it's co-located with ACM SIGCOMM conference which is a Tier-1 conference, it could be considered as a workshop in Tier-1 venue.

LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE 5 MOST IMPORTANT ONES											
No.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers	Tier	Number of citations
7	Incentives and Algorithms for Broadband Access Sharing	UCL	ACM SIGCOMM Workshop on Home Networks (HomeNets)	01/09/2010	ACM	New Delhi, India	2010	19-24	DOI: 10.1145/1851307.1851312	-	4
8	Fast Failure Recovery for Reliable Multicast-based Content Delivery	UNIS	International Conference on Network and Service Management (CNSM)	25/10/2010	IEEE/IFIP	Canada	2010	505-510	DOI: 10.1109/CNSM.2010.5691287	1	1
9	On the Interactions between Non-Cooperative P2P Overlay and Traffic Engineering Behaviors	UNIS	Global Communications Conference (GLOBECOM),	01/12/2010	IEEE	Miami, USA	2010	1-6	DOI: 10.1109/GLOCOM.2010.5683137	2	1
10	A Mutualistic Resource Pooling Architecture	UCL	Re-Architecting the Internet Workshop (ReArch)	01/12/2010	ACM	Philadelphia, Pennsylvania, USA	2010	3:1-3:6	DOI: 10.1145/1921233.1921237	-	3
11	Balancing by PREFLEX: Congestion Aware Traffic Engineering	UCL	Proceedings of the 10th international IFIP Conference on Networking	10/05/2011	IFIP	Valencia, Spain	2011	135-149	DOI: 10.1007/978-3-642-20757-0_7	1	2
12	Content mediator architecture for content-aware networks	TID	Future Network and Mobile Summit 2011,	15-17/6/2011	IEEE	Warsaw, Poland,	2011	1-8	ISBN: 978-1-4577-0928-9	-	9
13	An Empirical Study on the Interactions Between ALTO-assisted P2P Overlays and ISP Networks.	UNIS	The 36th IEEE Conference on Local Computer Networks (LCN)	4-7/10/2011	IEEE	Bonn, Germany	2011	719 - 726	DOI: 10.1109/LCN.2011.6115540	2	0
14	Towards Decentralized and Adaptive Network Resource Management	UCL	Network and Service Management (CNSM), 2011 7th International Conference on	24-28/10/2011	IEEE/IFIP	Paris, France	2011	296-301	DOI: 10.1007/978-3-642-13986-4_12	1	1
15	DACoRM: A Coordinated, Decentralized and Adaptive Network Resource Management Scheme.	UCL	Network Operations and Management Symposium (NOMS), 2012 IEEE	16-20 April 2012	IEEE	Hawaii, USA	2012	417 - 425	DOI: 10.1109/NOMS.2012.6211926	1	1

LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE 5 MOST IMPORTANT ONES											
No.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers	Tier	Number of citations
16	Chapter 9 - Towards Information-Centric Networking: Research, Standardisation, Business and Migration Challenges	PrimeTel	Media Networks: Architectures, Applications, and Standards, Editors: Hassna Moustafa, Sherali Zeadally,	05/2012	CRC Press	N/A	2012	163–186	DOI: 10.1201/b12049-12	-	1
17	Optimizing Server Power Consumption in Cross-Domain Content Distribution Infrastructures	UNIS	IEEE International Conference on Communications (ICC)	10-15/06/2012	IEEE	Ottawa, Canada,	2012	2628 - 2633	DOI: 10.1109/ICC.2012.6363659	2	3
18	An ISP and End-User Cooperative Intradomain Routing Algorithm	UNIS	Computers and Communications (ISCC), 2012 IEEE Symposium on	1-4/07/2012	IEEE	Cappadocia, Turkey	2012	289 - 294	DOI: 10.1109/ISCC.2012.6249310	2	0
19	Optimization of the decision process in Network and Server-aware algorithms	WUT	International Telecommunications Network Strategy and Planning Symposium (NETWORKS)	15-18/10/2012	IEEE	Rome, Italy	2012	1-6	DOI: 10.1109/NETWKS.2012.6381685	3	3
20	Cache "Less for More" in Information-centric Networks (Extended Version)	UCL	Elsevier Computer Communications, Special Issue on Information-Centric Networking	vol. 36, no. 7,	Elsevier	N/A	2012	758-770	DOI: 10.1016/j.comcom.2013.01.007	2	0
21	The content mediator architecture for content-aware networks	WUT	Special Issue of Journal Telecommunication Review and Telecommunication News	No. 8-9, September 2012	SIGMA NOT	N/A	2012	1192-1203	ISSN 1230-3496	-	0
22	Internet-scale Content Mediation in Information-centric Networks	UCL	Annals of Telecommunications, special issue on Networked Digital Media	Vol. 68, no. 3-4,	Springer	N/A	2013	167-177	DOI: 10.1007/s12243-012-0333-8	2	3
23	CCTCP: A Scalable Receiver-Driven Congestion Control Protocol for Content-Centric Networking	UCL	IEEE International Conference on Communications (IEEE ICC) 2013	9-13 June 2013	IEEE	Budapest, Hungary	2013		N/A	2	1

LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE 5 MOST IMPORTANT ONES											
No.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers	Tier	Number of citations
24	A Toolchain for Simplifying Network Simulation Setup	UCL	ICST Conference on Simulation Tools and Techniques (SIMUTOOLS) 2013	5-7 March 2013	ACM	Cannes, France	2013		N/A	2	2

Table 5-2: List of dissemination activities

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Presentation	UCL	Towards Future Self-managed Content-centric Networks	19/01/2010	Brussels, Belgium	Scientific Community, Industry	30	Europe
2	Presentation	TID	Content Mediation for Efficient Traffic Distribution	19/01/2010	Brussels, Belgium	Scientific Community, Industry	30	Europe
3	Presentation	UNIS	Thoughts on Future Networking and Network Management for Ubiquitous Media Delivery	19/01/2010	Brussels, Belgium	Scientific Community, Industry	30	Europe
4	Presentation	UCL	Future Content Networks: Network-related Research Issues	20/01/2010	Brussels, Belgium	Scientific Community, Industry	30	Europe
5	Presentation	TID	Content Mediator Architecture for Content-aware Networks	03/02/2010	Brussels, Belgium	Scientific Community, Industry	30	Europe
6	Presentation	TID	Internal COMET presentation for Telefónica	12/02/2010	Madrid, Spain	Industry	20	Spain
7	Presentation	ICOM	Standardization Overview at ETSI-MCD group meeting	22/02/2010	Nice, France	Industry	40	Europe
8	Brochure	TID	Networked Media – Current Research, Results and Future Trends	23/02/2010		Scientific Community, Industry		Europe
9	Web announcement	PRIMETEL	Web announcement of COMET project in PrimeTel's website	23/02/2010	Limassol, Cyprus	Industry, Media		Cyprus
10	Web announcement	PRIMETEL	Description of COMET project in PrimeTel's website	23/02/2010	Limassol, Cyprus	Industry, Media		Cyprus

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
11	Web announcement	TID	Web announcement of COMET project in TID's website (English and Spanish)	01/03/2010	Madrid, Spain	Industry, Media		Spain
12	Web announcement	ICOM	Web announcement of COMET project in ICOM's website (English and Greek)	01/03/2010	Athens, Greece	Industry, Media		Greece
13	Press release	TID	Issued Press release	01/03/2010	Madrid, Spain	Industry, Media		Spain
14	Press release	PrimeTel	Issued Press release	01/03/2010	Limassol, Cyprus	Industry, Media		Cyprus
15	Press release	ICOM	Issued Press release (English and Greek)	01/03/2010	Athens, Greece	Industry, Media		Greece
16	Presentation	UCL	The Content Mediation Approach Towards Future Information-Centric Networks	09/03/2010	Sophia Antipolis, France	Scientific Community, Industry		Europe
17	Web announcement	ICOM	1st draft of Industrial Dissemination List (IDL)	09/04/2010	Athens, Greece	Industry, Media		Europe
18	Presentation	UCL	Future Media Internet Architecture: Network-related Issues	14/04/2010	Valencia, Spain	Scientific Community, Industry	200	Europe
19	Press release	PrimeTel	Press Release published in SIGMALIVE.com	17/06/2010	Limassol, Cyprus	Industry, Media		Cyprus
20	Press release	PrimeTel	Press Release published in the Haravgi newsletter	24/06/2010	Limassol, Cyprus	Industry, Media		Cyprus
21	Press release	PrimeTel	Press Release published in the Politis newsletter	30/06/2010	Limassol, Cyprus	Industry, Media		Cyprus
22	Press release	PrimeTel	Press Release published in the Simerini newspaper	09/07/2010	Limassol, Cyprus	Industry, Media		Cyprus
23	Brochure	TID	FMN Cluster Report on research challenges	08/09/2010		Industry		Europe

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
24	Liaison	TID	1st COMET-ENVISION liaison meeting	28/09/2010	Brussels, Belgium	Scientific Community, Industry	10	Europe
25	Presentation	UCL	Future Media Internet Architecture: Evolutionary and Revolutionary Approaches	28/09/2010	Brussels, Belgium	Scientific Community, Industry	50	Europe
26	Video	TID	Video of the COMET project for the ICT 2010	29/09/2010	Brussels, Belgium	Scientific Community, Industry	200	Europe
27	Questionnaire	TID	NEM Standardization Survey	01/10/2010		Scientific Community, Industry		Europe
28	Video	TID	Video of the COMET project for the NEM Summit	13-15/10/2010	Barcelona, Spain	Scientific Community, Industry	200	Europe
29	Presentation	WUT	Content Aware Networks at ITU Workshop on The Networks of the Future, Warsaw	16/11/2010	Warsaw, Poland	Scientific Community	30	Global
30	Presentation	TID	Concertation Meeting - COMET - Project update 2010	29/11/2010	Brussels, Belgium	Scientific Community, Industry	30	Europe
31	Liaison	TID	Meeting with nextMedia	10/12/2010	Madrid, Spain	Industry	10	Europe
32	Presentation	ICOM	FI architecture & content-aware networks	16/12/2010	Ghent, Belgium	Scientific Community, Industry	200	Europe
33	Presentation	ICOM	Information Centric Networking	18/02/2011	Leicester, UK	Industry	40	UK
34	Presentation	UCL	The COMET Architecture: High-level Description	14/04/2011	Trento, Italy	Scientific Community, Industry	50	Europe

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
35	Presentation	TID	COntent Mediator architecture for content-aware nETworks (2011 April Update)	14/04/2011	Trento, Italy	Scientific Community, Industry	50	Europe
36	Presentation	TID	ICN naming, delivery and business models	18/05/2011	Budapest, Hungary	Scientific Community, Industry	40	Europe
37	Presentation	UCL	Information-Centric Networking: Overview, Current State and Key Challenges	18/05/2011	Budapest, Hungary	Scientific Community, Industry	40	Europe
38	Workshop	ICOM	Information Centric Networking	18/05/2011	Budapest, Hungary	Scientific Community, Industry	40	Europe
39	Presentation	UCL	IEEE/IFIP IM 2011 - Information-Centric Networking: Overview, Current State and Key Challenges	23/05/2011	Dublin, Ireland	Scientific Community	50	Global
40	Brochure	ICOM	Project Impact Factsheet	07/06/2011		General Public		Global
41	Seminar	UCL	UCL EE Seminar Series – Content Resolution and Delivery in Information-centric Networks	10/06/2011	London, UK	Scientific Community	20	UK
42	Presentation	UCL	IEEE WoWMoM 2011, Information-Centric Networking: Overview, Current State and Key Challenges	20/06/2011	Tucca, Italy	Scientific Community	40	Global
43	Presentation	UCL	IEEE ISCC 2011, Information-Centric Networking: Overview, Current State and Key Challenges	28/06/2011	Corfu, Greece	Scientific Community	40	Global
44	Presentation	ICOM	Presentation of COMET project to Mmlab, AUEB	06/07/2011	Athens, Greece	Scientific Community	10	Greece
45	Presentation	UNIS	COMET project achievements presentation to FP7 projects EVANS and PURSUIT	20/07/2011	UK	Scientific Community, Industry	20	UK

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
46	Liaison	TID	2nd COMET-ENVISION liaison meeting	15/09/2011	Limassol, Cyprus	Scientific Community, Industry	30	Europe
47	Presentation	UCL	Information-Centric Networking: Overview, Current State and Key Challenges at PURSUIT Plenary meeting	20/09/11	Athens, Greece	Scientific Community, Industry	20	Europe
48	Internet Draft	ICOM	Catalogue of Advanced Use Cases for Content Delivery Network Interconnection (Internet Draft)	24/10/2011	Taipei, Taiwan	Industry		Global
49	Liaison	TID	FIA October 2011	25/10/2011	Poznan, Poland	Scientific Community, Industry	200	Europe
50	Presentation	UCL	Information-Centric Networking: Overview, Current State and Key Challenges	26/10/11	Paris, France	Scientific Community, Industry	40	Global
51	Liaison	TID	3rd COMET-ENVISION liaison meeting	09/11/2011	London, UK	Scientific Community, Industry	10	Europe
52	Workshop	TID	Coment-Envision joint Workshop Future Media Distribution Networks	10-11/11/2011	Slough, UK	Industrial and Academic	40	Europe
53	Presentation	UCL	CURLING: Content-Ubiquitous Resolution and Delivery Infrastructure for Next Generation Services	11/11/2011	Slough, UK	Scientific Community, Industry	40	Europe
54	Presentation	UCL	Information-Centric Networking: Introduction and Key Issues	11/11/2011	Slough, UK	Scientific Community, Industry	40	Europe

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
55	Presentation	TID	COMET, the Decoupled Approach: Mediating between Content Producers and Consumers	11/11/2011	Slough, UK	Scientific Community, Industry	40	Europe
56	Press Release	PrimeTel	Press release in Primetel's magazine "PrimeNews"	01/12/2011	Limassol, Cyprus	Industry, Media		Cyprus
57	Presentation	TID	Summary of Coment-Envision joint Workshop Future Media Distribution Networks	12/12/2011	Brussels, Belgium	Scientific Community, Industry	15	Europe
58	Presentation	TID	COntent Mediator architecture for content-aware nETworks (2011 Update)	12/12/2011	Brussels, Belgium	Scientific Community, Industry	15	Europe
59	Conference	ICOM	"Connected TV and Beyond" presentation at the 9th Annual IEEE Consumer Communications & Networking Conference	14/01/2012	Las Vegas, USA	Scientific Community	40	Global
60	Presentation	UNIS	"Information-Centric Networking Approaches in the COMET Project" presentation at the 4th EU-Japan Symposium on New Generation Networks and Future Internet, Tokyo	19/01/2012	Tokyo, Japan	Scientific Community, Industry	50	Europe and Asia
61	Presentation	ICOM	The COMET Project at the SESERV Workshop	31/01/2012	Athens, Greece	Scientific Community, Industry	50	Europe
62	Liaison	ICOM	IETF 83	25-30/03/2012	Paris, France	Industry		Global
63	Technical Specification	ICOM	"ICN and CDN-I" – Contribution to ETSI TS 102 990 of ETSI MCD CDN-I	31/03/2012		Industry		Europe

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
64	Presentation	UCL	"Caching in Information-Centric Networks: Current Trends and Future Challenges" at King's College	18/04/2012	London, UK	Scientific Community	20	UK
65	Presentation	UNIS	An Evolutionary ICN Approach for Popular Content Distribution at Internet Scale at theFlexible Networks Workshop - University of Surrey, UK	25/04/2012	Guildford, UK	Scientific Community, Industry	30	UK
66	Presentation	UCL	Caching in Information-Centric Networks: Current Trends and Future Challenges at theFlexible Networks Workshop - University of Surrey, UK	25/04/2012	Guildford, UK	Scientific Community, Industry	30	UK
67	Liaison	TID	FIA Aalborg 2012	10/05/2012	Aalborg, Denmark	Scientific Community, Industry	200	Europe
68	Conference	UCL	"The Information-Centric Networking Challenge: Background, Open Issues and Research Directions" tutorial at 24th International Teletraffic Congress (ITC-24)	15/05/12	Krakow, Poland	Scientific Community	20	Global
69	Presentation	UCL	Keynote speech on "Information-Centric Networking and In-Network Caching" at IEEE/ACM International Teletraffic Congress (ITC-24) 2012	06/09/12	Krakow, Poland	Scientific Community	20	Global
70	Demonstration	WUT	The COMET Decoupled Approach Prototype	12-14/09/2012	Warsaw, Poland	Scientific Community, Industry	100	Europe
71	Conference	WUT	Content Aware Networks at Polish ICT Conference	13/09/2012	Warsaw, Poland	Scientific Community	100	Europe

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
72	Liaison	TID	Future Networks 10th FP7 Concertation	10-11/10/2012	Brussels, Belgium	Scientific Community, Industry	40	Europe
73	Liaison	ICOM	NEM Summit	17-18/10/2012	Istanbul, Turkey	Industry	200	Europe
74	Workshop	UCL	Joint COMET-PURSUIT Workshop	29-30/10/2012	London, UK	Scientific Community, Industry	40	Europe
75	Demonstration	TID	The COMET Decoupled Approach Prototype	29-30/10/2012	London, UK	Scientific Community, Industry	40	Europe
76	Presentation	ICOM	Is ICN going to make it to deployment?	29-30/10/2012	London, UK	Scientific Community, Industry	40	Europe
77	Liaison	TID	4th COMET-ENVISION liaison meeting	30/10/2012	London, UK	Scientific Community, Industry	10	Europe
78	Press Release	TID	Issued Press Release	07/12/2012	Madrid, Spain	Industry, Media		Spain
79	Demonstration	TID	The COMET Decoupled Approach Prototype at TID premises	12/12/2012	Madrid, Spain	Industry	40	Spain
80	Paper	TID	CCN and CDNs whitepaper	13/12/2012	Madrid, Spain	Industry	40	Spain
81	Press Release	ICOM	Issued Press Release	03/01/2013	Athens, Greece	Industry, Media		Greece
82	Internet Draft	UCL	IRTF ICNRG Research Challenges	13/01/2013		Scientific Community, Industry		Global

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
83	Presentation	UCL	CURLING: Content-Ubiquitous Resolution and Delivery Infrastructure for Next Generation Services at PURSUIT Workshop, University of Essex	23/01/2013	Essex, UK	Scientific Community	40	UK
84	Presentation	ICOM	"Is ICN going to make it to deployment?" presentation at the ICNRG interim meeting, Kista, Stockholm, Sweden, February 14-15, 2013	14-15/02/2013	Stockholm, Sweden	Industry	40	Global
85	Article	PrimeTel	Primetime Magazine article	01/03/2013	Limassol, Cyprus	Industry, Media		Cyprus
86	Internet Draft	ICOM	IRTF ICNRG Baseline Scenarios	10/03/2013		Scientific Community, Industry		Global
87	Presentation	TID	The CCN Paradigm at Telefonica	21/03/2013	Madrid, Spain	Industry	40	Spain

6 Exploitation measures and plans

6.1 Overview and selection of exploitable foreground items

The exploitation strategy of the COMET consortium relies on two main factors; the foregrounds to be exploited ("what") and the partners that will exploit them ("who"). The "what" part describes what the project has produced throughout its 3-year duration that could be exploited and what is its potential socio-economic impact, while the "who" part defines the partner's profile, expertise and capability, as well as its plans and methodology for exploiting the item during and after project's completion.

The project's achievements have been documented in all respective deliverables of WP 1-6 and disseminated to prestigious conferences and events. Algorithms were specified for both COMET approaches, models and simulations were designed to study them, and prototypes were developed to prove and demonstrate the COMET concept. A long list of exploitable foreground items was produced; however the consortium has selected the most important and representative ones, based on certain criteria: (1) partners' commercial and scientific interest and incentives to exploit them, (2) items' impact to the consortium, the ICN research field and society in general, and (3) items' current and further scientific impact, reflected by the tier of the conferences and their number of citations, as presented in section 5.

In this sense, certain categories were identified including the key conclusions and advancement of knowledge provided by the project and following the engineering design process "design-simulate-implement-test":

- **Advancement of knowledge**, highlighting advancement in knowledge and high-impact recommendations and conclusions,
- **Algorithms and mechanisms**, including all project's suggested algorithms and mechanisms,
- **Models**, describing all the designed models and methods to study the aforementioned approaches,
- **Simulators**, introducing the simulators implemented to prove the feasibility of algorithms and mechanisms,
- **Prototypes**, including all developed prototypes that could be further exploited and deployed in the Internet, and finally,
- **Testbed**, describing the infrastructure used to test the COMET prototypes.

Under these categories, 14 exploitable foreground items were selected, as presented in section 3.3. The COMET consortium identifies the "ICN feasibility in Internet-scale" and "Cache less for more" recommendations as the key project conclusions, providing incentives to Internet stakeholders to deploy the COMET solution and adopt the specified in-network caching mechanisms, as well as continue their ICN research. Certain algorithms and mechanisms were designed and specified to support these conclusions, also published in high-tier conferences and journals, as well as models and simulators to study their feasibility. Finally, the industrial partners have chosen 3 of the implemented prototypes, as the most potential and interesting for commercialization, especially due to their potential for deployment as standalone components in existing network infrastructures and services and their socioeconomic impact.

In the following sections, for each exploitable foreground item we provide the following:

- **Type**, as one of the following:
  - General advancement of knowledge,
  - Commercial exploitation of R&D results,
  - Exploitation of R&D results via standards,

   - Exploitation of results through EU policies,
   - Exploitation of results through (social) innovation.
- **Purpose**, briefly describing the exploitation foreground and the reasoning behind its exploitation by one or more COMET partners,
- **Exploitation**, defining the interested partners' profiles and capability to exploit the item, as well their plans and methodology,
- **Further Research**, describing any further work required for the item to be exploited, and the research opportunities that could arise,
- **Socioeconomic Impact**, providing each partner's view on the exploitation foreground impact on European society and economy.

The COMET partners are divided into industrial and academic. Generally, industrial partners focus on the demonstration and commercialization of the developed prototypes and transfer of know-how to technical departments through seminars and workshops, while academic partners exploit the project's scientific results by papers, courses, doctoral and master theses, as well as new research projects.

The following sections present all COMET partners' measures and plans for the aforementioned exploitation foreground items.

6.2 Advancement of knowledge

6.2.1 ICN feasibility at internet-scale

Type:

General advancement of knowledge

Purpose:

The analyses, simulation experiments and trials with the COMET prototype performed in the federated testbed confirmed that there should be no barriers in deploying both COMET approaches, i.e. the decoupled and the coupled, at internet-scale network. This knowledge motivates further research on both approaches and motivates transition from the proof of concept phase to the field trials phase.

Exploitation:

The feasibility for ICN deployment in the Internet-scale network is one of the main concerns in the research community working on ICN solutions. The obtained results for the coupled and the decoupled approach confirmed that both approaches are feasible for deployment. However, the performed studies identified some constraints and potential advantages. This knowledge could be exploited in: (1) forthcoming publications pointing out constraints and advantages of both approaches, (2) further research on ICN system, especially on identified constrains, (3) possible transition from the proof of concept phase to the field trials phase. The academic partners are committed to continue their research in the ICN area, by MScs, PhDs and future research projects. On the other hand, the industrial partners of COMET will proceed with the pre-commercialization of the developed prototype, by continuing their research, improving performance issues and enhancing certain functionalities that are required to reach the deployment phase. Such measures are also described in section 6.6, related to the exploitation of the prototypes.

Further Research:

Further research should focus on technological constraints, quantitative analysis of COMET system entities, as well as specification of recommendations for COMET system deployment. Moreover, some further improvements, especially in content resolution phase, are possible, e.g. by applying:

(1) caching mechanisms in the client CME for storing content/authoritative records, paths and servers' load and (2) smart querying algorithms for the retrieval of servers load and routing paths.

Socioeconomic Impact:

The results of ICN feasibility studies may have impact on both the research community and the possibility for COMET prototype commercialization. Nowadays, there are certain concerns in the scientific community and Internet stakeholders regarding the scalability and performance of ICN solutions, compared to existing content delivery services, e.g. CDNs. In addition, at this moment the incentive for Network Operators and Content Providers to adopt and deploy such solutions seems unclear. The aforementioned recommendation could trigger further research in the scientific community, and encourage Internet market stakeholders to consider such solutions and take part in the content distribution. The adoption of ICN solutions would be beneficial for content consumers who would experience higher-quality services. New market opportunities would require further academic, engineering and market research, resulting in future research projects, MScs and PhDs, as well as possible economic gains and new job opportunities in the industrial sector.

6.2.2 "Cache less for more" recommendation

Type:

General advancement of knowledge

Purpose:

In ICN environments, contents are explicitly named and therefore, can be cached in network devices, such as network routers. Some initial proposals on in-network caching (such as [16]) have proposed that contents are cached in every network router they traverse. This clearly causes redundancy as contents are replicated multiple times along the delivery path. We have observed that this is not an optimal approach to in-network caching and have evaluated alternative approaches, where contents are not replicated in every node along the delivery path. As explained further below, in COMET we have designed two different approaches to in-network caching, where copies of contents are replicated according to specific criteria. According to our evaluations, we have shown that our proposals improve significantly the performance of in-network caching.

Exploitation:

The recommendation is especially useful in network planning and design to ensure the deployed network meets the needs of both the subscribers (e.g., content delivery latency) and operator (e.g., costs) while maintaining a good "green" operation mode (see socioeconomic impact). Network designers can now have another dimension of flexibility in designing their networks both for long/short-term planning and also for IT asset sourcing.

Networking equipment producers (e.g., Cisco, Juniper) can also take this recommendation into account when designing their next generation products to enable selective caching mechanisms. This adds a new feature in their product(s).

Our techniques have received wide attention from researchers working in the area and by projects that target information-centric networking environments. We expect that our proposals will be used to advance the state of the art and trigger further research in the area. This has already been evident from researchers who are implementing our proposals in their simulators in order to be evaluated against alternative approaches.

The abovementioned parties can already exploit this recommendation now.

Universities can also exploit this new knowledge by means of absorbing the recommendation into their teaching courses. Furthermore, student projects can also be based on this new finding. In fact, UCL, UniS and WUT have already started to exploit this foreground. For example, there are already several master-level projects being offered in UCL that are based on this foreground over the past couple of years. One of such projects has won the best student project of the year in 2011 in the department.

Further Research:

The design and evaluation of our proposals ([12][13][18]) constitute the first steps towards the realisation of the most efficient approach to in-network caching. Several parameters, such as the network topology or the traffic characteristics, affect the performance of the techniques and algorithms proposed. That said, further research is needed in order to quantify the tradeoffs of each setup and make decisions on the most appropriate approach to in-network caching.

Socioeconomic Impact:

Besides enhancing network related performances, the “cache less for more” in-network caching recommendation, if adopted, can help reduce energy consumption as it will significantly decrease caching (insert/delete) operations especially when deployed in a large network as well as server operations. For instance, based on our investigation, the centrality-based caching approach [13][18] can reduce up to approximately 70% of caching operation overhead when compared to the conventional indiscriminate caching such as that proposed in [16]. Thus, it contributes to the greening of the environment.

The recommendation has also been acknowledged (by the IFIP Networking Best Paper Award committee) to have wider impact on the general research of in-network caching. It has the potential to trigger further research and corresponding projects in the area. Furthermore, the academic partners of the project and especially UCL has already given 5 MSc courses in the area of selective in-network caching. UCL has also funded a PhD in the area and plans to advertise at least another two new PhDs in the coming year.

6.3 Algorithms and mechanisms

6.3.1 Gossip-based content resolution mechanism

Type:

General advancement of knowledge

Purpose:

In COMET, we investigate the feasibility of a gossip-based content resolution mechanism that works at the Internet scale with graceful support of receiver-driven multicast over multiple ASes. Our hop-by-hop approach was inspired by the DONA [17] approach which exploits the business relationship between autonomous domains uniquely presence in the Internet topology. We designed the CURLING mechanism [19] (i.e., the coupled approach in the COMET project) which includes the content publication, resolution and delivery mechanisms to address the full cycle of the content consumption process. In addition, a set of routing optimization techniques have also been developed which can be applied after a successful inter-domain resolution.

Exploitation:

Our hop-by-hop hierarchical content resolution mechanism for Internet-scale content distribution has already been recognized as one of the main content dissemination approach in ICNRG [23]. It is thus a potential content distribution approach for the future Internet-scale content ecosystem. Content distribution network operators and ISPs may exploit this foreground.

Besides ICNRG, this foreground has already gathered significant attention from various research groups (especially those working in the ICN areas). Thus, it is readily exploitable for future research in ICN.

Universities again can use this to enhance their postgraduate-level teaching courses especially topics related to content resolution approaches which has mainly focused on DNS and DHTs so far. UCL, UNIS and WUT are already planning to include such material in their courses in the coming semester.

Further Research:

There are already indications in the literature that the business relationships between various ASes in the Internet are evolving. For example, there is some evidence that the Internet is becoming "flatter" as opposed to the conventional view of it being highly hierarchical. Such evolution may have subtle impact to our mechanism and thus, should be further investigated.

In addition, there is also the question of the overall approach (i.e., DHT vs gossip-based). A comprehensive comparison study is deemed appropriate. In fact, there is already some initial work beginning to compare the two approaches [21][22].

Socioeconomic Impact:

The current Internet relies on DNS (third-party) to resolve user requests. If adopted, our hop-by-hop content resolution approach will enable substantially more active involvement from network operators (ISPs) in the content-based Internet business marketplace. This added dimension will increase competition between autonomous domains especially when our approach allows both network operators and content prosumers the options to filter/scope their publication and/or requests. As such, we see a more competitive content marketplace to emerge from such ecosystem which will (1) provide more incentive for network operators to engage in the content marketplace, (2) push down the cost of content consumption, (2) create new opportunities / lower the entry barrier for new content providers into the content distribution market and (3) provide better overall performance in content access.

6.3.2 Multi-criteria server and path selection algorithm

Type:

General advancement of knowledge

Purpose:

The multi-criteria server and path selection algorithm was designed to optimise resources used for content delivery in ICN systems by exploiting knowledge about the servers' load and network conditions. The algorithm has been designed based on achievements of the Multiple Criteria Decision Analysis (MCDA). It belongs to the class of algorithms that use some a priori knowledge about the problem in order to select the effective solution.

Exploitation:

The proposed multi-criteria server and path selection algorithm has been recognized as efficient algorithm for ICN systems, which allows improving the efficiency of content delivery. The proposed algorithm jointly with the performance evaluation results has been presented on conferences [28], [27]and published in journals[26], [29]. The received feedback from researchers and industry, e.g. AKAMAI, was positive.

The designed multi-criteria decision algorithm can be exploited in other content delivery systems, like CDNs, CAN, P2P or other application layer system to select the best content source. Up to now, our algorithm has been exploited in two research projects focused on ICN systems. In the ALICANTE project, the algorithm was used at the application layer to rank available content sources and select the preferred one, see [27]. On the other hand, the algorithm was exploited to rank available content source in the PICAN network designed in the Future Internet Engineering (FIE) project.

From the academic partner's perspective, the designed algorithm is new knowledge which could be included in the courses, student projects, MSc and PhD theses and stimulate new research directions. For example, WUT has already exploited the proposed algorithm to update courses and as a base for MSc thesis defended in 2011 and PhD thesis planed for 2014.

Further Research:

The further research on multi-criteria decision algorithm will focus on dynamic adaptation of reference levels used in the ranking that tune the importance of some particular decision variable following the range of values in the set of candidate solutions. Such dynamic adaptation eliminates the need for a priori knowledge about the problem and simplifies algorithm configuration. The promising results published in [27] motivate our further research on such extensions.

Although, the multi-criteria decision algorithm was designed for the COMET system, it could be relatively easy adapted to other ICN systems. Therefore, we investigate the possibilities for algorithm exploitation in other WUT research areas where optimization based on heuristic algorithms is needed.

Socioeconomic Impact:

The multi-criteria decision algorithm improves effectiveness of the ICN in terms of: (1) better quality experienced by users (QoE), (2) improved system resource utilisation and (3) improved the load-balancing within the network and between servers. The gain from multi-criteria decision algorithm is especially visible in case of dynamically changing conditions, e.g. flash crowds. All these features lead to improved availability of content, reducing the risk of network congestion and server overload. From the economic perspective, the multi-criteria decision algorithm should allow ICN operator to: (1) increase income due to increasing number of satisfied consumers and reducing the number of rejected content requests, (2) reduce investments costs related to ICN infrastructure by optimal utilization of server and network resources, (3) improve overall system performance.

6.3.3 Multi-path and multi-criteria routing algorithm

Type:

General advancement of knowledge

Purpose:

The designed multi-path and multi-criteria routing algorithm offers two new features comparing to BGP-4 protocol: (1) multi-criteria (QoS) routing which allows routing entity to build routing paths taking into account the end-to-end QoS requirements related to supported classes of service and vectors of QoS parameters that characterise the links, and (2) multipath routing as routing entity calculates and advertises a number of routing paths going between any pair of source and destination domains.

Exploitation:

The single, shortest path paradigm assumed for the currently used routing protocols is commonly recognized as one of the fundamental limitations of the Internet. The proposed multi-path and multi-criteria routing algorithm could be exploited as a solution for relaxing this limitation. The very promising results related to the performance gain obtained by ICN thanks to using proposed multi-path and multi-criteria routing, which are presented in [9],[26], motivates WUT to: (1) exploit the current simulation and experimental results in forthcoming publications, (2) continue our research on multi-path, multi-criteria routing algorithmin the wider context of the Future Internet systems, and (3) investigate the possibility to adapt the algorithms for future projects.

From the academic perspective, the designed multi-path and multi-criteria routing algorithm is a new knowledge which could be included in the courses, student projects, MSc and PhD theses and stimulate new research directions. For example, WUT has already exploited the algorithm to update student projects and used it as a base for two MSc theses defended in 2011 and 2012 as well as PhD thesis planned for 2014.

Further Research:

The further research will focus on the optimization of the decision algorithm, adaptation to changing network conditions and routing performance evaluation under different objective functions. Moreover, we investigate how the multi-path, multi-criteria routing could be exploited in other network architectures, i.e. IP/MPLS, NGN and SDN.

Socioeconomic Impact:

The multi-path, multi-criteria routing algorithm allows overcoming limitations of the shortest path routing protocols currently exploited in the Internet. The multi-criteria feature increases the number of end-to-end routing paths that satisfies the QoS requirements. On the other hand, the multi-path feature, establish a number of routing paths between any pair of source and destination domains, which increases the throughput in the network and enables new traffic engineering mechanisms, e.g. path protection, path balancing.

From the economic perspective, the multi-path, multi-criteria routing algorithm should allow network operator to: (1) increase income due to increasing number of customers that experience satisfactory quality, (2) reduce investments costs related to network infrastructure by optimal utilization of network resources, (3) stimulate the competition between ISP to improve offered QoS (the domains that offers poor quality of service would be avoided at routing level), and (4) improve overall network performance and reliability.

6.3.4 Stateless packet forwarding mechanism

Type:

General advancement of knowledge

Purpose:

The stateless packet forwarding mechanism follows the source routing principle at the domain level and allows flexible selection of routing path for each data flow. It assumes that network nodes forward packets based on information about the selected path stored in the additional header attached to the original packet. As a result, nodes maintain only the neighbourhood (local) information, i.e., how to forward packet to the next node instead of keeping global prefixes in routing tables.

Exploitation:

The problems with exploding routing tables in IP routers and limitations coming from ossification of the IP protocol stack motivate research on new, open (programmable) and flexible data plane technologies. The stateless packet forwarding mechanism has been designed to these requirements. The positive conclusions obtained from the scalability evaluation [9] and performance experiments with the prototype implemented on Linux [11], motivates WUT to: (1) exploit the current analytical and experimental results in forthcoming publications, (2) continue our research on stateless packet forwarding mechanism in the wider context of the Future Internet systems, as well as (3) investigate the possibility to adapt the stateless forwarding for future projects.

Up to now, the stateless packet forwarding has been exploited in PICAN network designed in Future Internet Engineering (FIE) project. In this project, the modified version of stateless forwarding mechanism was implemented based on two hardware platforms, i.e. EzAppliance (the network processor experimental platform) and NetFPGA card [30]. This prototype allows concluding that the stateless forwarding mechanism is feasible for implementation in the hardware platforms and the complexity of packet processing in proposed mechanism is similar as the processing in IP router.

From the academic perspective, the designed stateless packet forwarding mechanism is a new knowledge which could be included in the courses, student projects, MSc and PhD theses and stimulate new research directions. For example, WUT has already exploited the algorithm to update student projects and used it as a base for two MSc theses defended in 2012 and 2013 as well as PhD thesis planned for 2014.

Further Research:

The further research will focus on extension the stateless forwarding mechanism for new features like multicast connections, content adaptation, and mobility support. Moreover, we investigate how the stateless packet forwarding could be exploited in future network technologies, i.e. SDN.

Socioeconomic Impact:

The stateless forwarding mechanism allows for: (1) flexible selection of routing path for each data flow enabling new traffic engineering algorithms, (2) openness for applying specific packet processing mechanisms within nodes, which support mobility, flow redirection, multicast, QoS, security, etc..

From the economic perspective, the stateless forwarding mechanism should allow network operator to: (1) increase income thanks to offering new services, (2) reduce investments costs related to network infrastructure by optimal utilization of network resources, (3) improve overall network performance and reliability.

6.3.5 In-network caching mechanisms

Type:

General advancement of knowledge

Purpose:

As discussed above, the first observation with regard to in-network caching in the course of the COMET project was the “cache less for more” design paradigm. Based on this, and given the fact that ubiquitous replication of contents is not optimal, we have designed two different approaches to in-network caching. Namely, the first approach is a centrality-based one, where contents are cached in the most central node(s) of each delivery path and thus resulting in a “directed” spreading of content towards the content consumers [13][18]. The second one is a probabilistic in-network caching approach, which takes a resource management view of the delivery path and applies replication rules accordingly [12].

Exploitation:

We expect that these two algorithms will be exploited by the research community to advance the state of the art in in-network caching environments. We have already initiated discussions with other projects, who are interested to implement our approaches in their own simulators and testbeds (e.g., CCNx) in order to evaluate their performance under different architectures. We expect more interest from other ICN projects as the field matures.

Further research:

The design principles of each of our approaches might fit to different settings in terms of traffic characteristics within a domain, topology of a domain, etc. Therefore, we consider that further research is necessary in order to find the best candidate approach (i.e., probabilistic or centrality-based) for different ISP networks. We have already built a simulation setup tool [15] that can test different caching algorithms under different topologies and traffic characteristics. We plan to make this simulator publicly available in order for other researchers to be able to experiment with our findings.

Expected Socioeconomic Impact:

The centrality-based technique and the probabilistic in-network caching algorithm have the potential to trigger further research and corresponding projects. Academic partners and especially UCL will exploit the knowledge gained during the past years in the area of in-network caching by giving MSc and PhD programs in the area, as also discussed above.

6.4 Models

6.4.1 In-network caching models

Type:

General advancement of knowledge

Purpose:

Information-Centric Networking enables transparent operation of in-network caching by identifying content chunks as they travel through the network. The new ubiquitous caching system has the potential to improve the performance of the network due to the on-path caching feature. On the other hand, deploying extra memory within the network imposes extra costs to ISPs. Therefore, the gain of this caching system has to be approximated in advance of investments. We have therefore, designed a model that approximates the gain of deploying memory in the network, and calculates the time that specific contents stay in caches [14]. Our evaluations have shown that our model is very accurate and that it can be used to approximate the caching time of specific contents.

Exploitation:

Our model has already received wide attention from the research community as it is the first theoretical model to approximate the behavior of the new caching system. We believe that as the field matures, more researchers will focus on the theoretical boundaries of information-centric networks, where our model can comprise a starting point for further investigation. Furthermore, the outcome of our model (i.e., the exact time that a specific content stays in a network cache) can be used as an evaluation metric. We are already in contact with researchers working on ICN projects who are implementing this model in their simulators and testbeds in order to evaluate the performance of their approaches to ICN.

Further research:

The initial version of our model applies to one specific caching approach, according to which contents get cached in every network node they traverse. We have extended our model to fit to other caching strategies too and have recently submitted a paper to the Elsevier Computer Networks Special Issue on ICN. We also plan to extend the model to find the instantaneous behavior of caches.

Socioeconomic Impact:

The mathematical model that we have built has the potential to trigger further research in the area of Information-Centric Networks and their mathematical modelling. Modelling the behaviour of the new system of in-network caches has already attracted one MSc student at UCL and more advanced theoretical modelling will be integrated in PhD studies that academic partners (and especially UCL) plan to advertise in this area.

6.4.2 ICN evaluation method

Type:

General advancement of knowledge

Purpose:

The performance and scalability evaluation of ICN system requires development of simulation/analytical models of ICN processes and definition of the large scale model of video content system. In COMET, we defined the model the content resolution process as an open queuing network where particular COMET entities play the role of servers fed by sequence of tasks imitated by content requests. Moreover, we defined large-scale network model for ICN system which takes into account: (1) a large-scale model of Internet topology, (2) content server location and characteristics, and (3) content characteristics and distribution.

Exploitation:

The ICN evaluation method designed in COMET can be exploited for evaluation other content delivery systems, like CDNs, CC, P2P. In particular, the large scale model of video content system presented in [26] has gained attention as an exploitable foreground. On the other hand, the successful evaluation of content resolution process by exploiting defined model, motives WUT to: (1) exploit the current simulation and experimental results in forthcoming publications, (2) exploit large scale model of video content system for research purposes (3) extend the content resolution model and evaluation other ICN systems and (3) investigate the possibility to adapt the resolution model for evaluation signalling systems of other network technologies, e.g. NGN.

From the academic partner's perspective, the designed models constitute a new knowledge which could be included in the courses, student projects, MSc and PhD theses and stimulate new research directions. For example, WUT has already exploited the proposed evaluation method as a base for MSc theses defended in 2013 and will continue studies towards the PhD.

Further Research:

The further research will focus on updating the large scale model of video content system following the recent changes related to Internet topology (based on CAIDA reports), the content servers localization and content characteristics. On the other hand, the research on evaluation method will focus on improving the simulation performance and accuracy. In particular, the validation of the model accuracy under the heavy load condition and correlation between sub processes is still the open issue.

Socioeconomic Impact:

The developed evaluation method and models could be used by other researchers. The large scale model of video content system make possible comparing the performance of different ICN system in the same reference scenario. So, if the model becomes widely accepted, it may have significant impact on the research community working on ICN systems.

The proposed content resolution evaluation method allows simulating the behaviour of the ICN system deployed in the large scale network. Therefore, the method may be helpful for ICN system designers to identify the potential bottleneck in the planned deployment of ICN system.

6.5 Simulators

6.5.1 ICN simulators

Type:

General advancement of knowledge

Purpose:

Simulation is often used as part of the engineering design process to test theories, concepts and ideas before real-world deployment. For this purpose, we have implemented several simulators in the course of the COMET project for the investigation of different aspects and mechanisms.

- UCL has developed simulators that implement the in-network caching algorithms and techniques that have been developed throughout the course of this project (i.e., probabilistic caching [12]and centrality-based caching [13][18]). The simulator is based on our *Fast Network Simulation Setup* (FNSS) tool [15]. The simulator also includes the implementation of other caching approaches, such as the ubiquitous caching approach. The purpose is to further evaluate and compare the performance of several different approaches to in-network caching. We also plan to make the simulator publicly available, in order to allow researchers working in this area to experiment with our protocols and also extend it with their own findings and compare the performance.
- UNIS has developed an object-oriented Matlab-based simulator for the performance evaluation of the CURLING paradigm within large-scale topologies. Currently the simulator offers basic functions including content resolution (both random and broadcast modes), and content delivery (including routing optimization exploiting multi-homing and peering links between domains).
- WUT has developed three simulators. The first simulator has been designed for performance evaluation of multi-criteria decision algorithm. It simulates the content

request arrivals and analyzes the content delivery performance for each content request in the large scale video content model. The second simulator is dedicated for performance evaluation of multi-path, multi-criteria routing algorithm. It simulates behavior of routing entities and measures performance in terms of the number of routing paths satisfying QoS constraints. The third simulator has been developed for evaluation the content resolution procedure. It models the COMET system as open queuing network, where particular COMET entities play the role of servers. The queuing network is fed by the arrivals of content requests. Each request initiates the sequence of tasks executed in different servers. The input data for this model were obtained from the experiments carried out on the COMET prototype deployed over the federated testbed.

Exploitation:

UCL's simulator is going to be made publicly available, thus it is expected that it will receive attention and will trigger further research in the area. We have already received interest from researchers who intend to work with our protocols and therefore, this tool will give them the opportunity to experiment and compare the performance of our findings.

Universities may exploit our publicly available simulators for their courses and research activities. UCL plans to design course assignments based on the caching simulator to provide students the opportunity to learn and understand the different caching techniques by conducting simulations on their own. UniS plans to extend the current CURLING simulator for future research topics, including resilience and security issues in inter-domain content distribution. Finally, WUT will make the simulators available for ongoing and future MSc and PhD theses in the ICN field.

Further research:

We plan to further extend our simulators to include the implementation of our theoretical model, which approximates the proportion of time that contents stay in network caches (see item above). We also plan to implement caching approaches that have been proposed by other researchers, in order to perform a comprehensive performance evaluation of in-network caching techniques. With respect to the CURLING simulator, we plan to extend the functionality to allow for ICN-based security mechanisms to be researched and developed.

Socioeconomic Impact:

Our simulators will enable other researchers to experiment with our protocols, and allow for new protocols to be implemented with ease, so as to allow for comparison and further enhancement of the concepts developed in this project. Furthermore, the tools will be made available to new MSc and PhD students in order to enhance the quality of their projects and studies and make their integration in the area progress faster.

6.6 Prototypes

6.6.1 ICN controller and forwarding prototype

Type:

Commercial exploitation of R&D results

Purpose:

The prototype configures and controls specialised network elements which can capture specific traffic flows and ensure QoS. In such sense, it would help network operators to utilise the network links they manage in a more effective manner, saving bandwidth, energy and OPEX, since most of these operations would be performed in an automatic/on the fly manner without resorting to external operators.

As a network operator, Telefónica will investigate whether this prototype could be deployed in its network and/or integrated to existing services. ICOM will produce a repackaged version of the prototype to be initially demonstrated in relevant technical and market departments. In the positive scenario, it will investigate whether it could be integrated in existing company products and services or add a new commercial product in company's market portfolio. In addition, ICN know-how will be transferred to technical departments, to enrich their knowledge.

Exploitation:

Two industrial partners have presented an interest to exploit the ICN controlling and forwarding prototype, with their profile, plans and methodology presented below:

- Telefónica is a Network Operator of almost global reach, offering data carrying services to content and services providers and even operating its own content distribution services. TID is involved in COMET through its Network Automatisation and Dynamisation Initiative belonging to the TPI Unit (Transversal Projects and Innovation).

  This prototype is intended to be used as a pilot to foster the transmission of specialised data services with warranted QoS. The work to be done in the following months is to identify which data services would profit from this prototype, which would be the best means of deployment in the current Telefonica Network and which extra requirements/features should be added to the prototype. With this aim in mind, meetings with the units in charge of managing Telefonica's network will be held to made them aware of the prototype advantages and obtain feedback, not only for the prototype but also for the ICN concepts.

  Decision on deployment will depend on the final assessment of COMET outcomes by the Strategy Department embedded in Telefonica TPI.

- ICOM is a leading regional telecommunication vendor and integrator, operating in EEMEA, CIS, and APAC regions, which provides telco products, solutions, and services, partnering with major vendors and network providers. ICOM is involved in the COMET project through its Telco Software Business Unit – R&D Unit.

  Members of the R&D Unit are currently working on revising and repackaging the controller and forwarding prototype, aiming to demonstrate it internally. The desired scenario is that the management of the department will decide that it can be incorporated into the company's IPTV & Digital Content Service platform (fs|cdn) to improve its QoS and customers' QoE.

  Prototype demonstration will be also held in the Marketing Department, aiming to assess its pre-commercialization possibility. Its potential to be added in company's market portfolio will rely on market research and company's partnerships.

  In addition, ICOM is planning to organize internal ICN seminars within 6 months after project completion, to transfer the obtained knowledge, e.g. ICN principles, implementation and integration procedures, to employees of its technical departments. More specifically, the targeted areas will be, the Wireless Business Unit, Network Management System department and the ICT SERVICES & SOLUTIONS Business Unit's Data Center & IT Infrastructure Optimization department.

Further research:

Research has to continue in order to make these elements aware about new streaming/distribution protocols, as well as make them able to report network conditions to the control elements, so restoring/avoidance measures can be adopted in case of element failure, enabling service to be maintained. An important feature that has to be included in the prototype is the capability of interacting with the current provision systems in operation in Telefonica, so any required configuration information can be extracted from those existing systems.

For the enhanced and repackaged version of the prototype, ICOM is currently investigating whether existing wide-spread protocols or solutions could be integrated into the prototype. More specifically, the currently developed prototype uses the Handle protocol for its content resolution procedure, and custom protocols and mechanisms for the routing awareness mechanism, and configuration of the forwarding module. Instead, DNS, BGP and OpenFlow protocols could be enhanced into the prototype to ensure its compatibility and feasible adoption to network and content providers' existing infrastructure. Besides engineering, further market research is required to evolve the repackaged prototype into an exploitable commercial product.

Socioeconomic impact:

To ensure that flows are transmitted with warranted QoS is one of the most crucial aspects of content transmission and therefore the deployment of this prototype will entail a general improvement on final user quality perception for this sort of services. In such sense, Telefónica could adopt a more competitive position in comparison to other network operators, by offering a better quality either for the user of its own content distribution services or for the content providers which have chosen Telefónica as their ISP.

The integration of the repackaged prototype into ICOM's IPTV platform or its evolution into a commercial product would require further engineering work, including design, development and testing. ICOM may even hire new or utilize employees already working in coming to the end of their life projects. In the same sense, ICN seminars would evolve into new services and projects that would require new teams of people to support them. In any case this has positive results regarding unemployment.

6.6.2 Server and network monitoring prototype

Type:

Commercial exploitation of R&D results

Purpose:

This prototype obtains information about servers' health belonging to a server farm in a consolidated status so that a load balancer (or other external elements) could use it for refining its decision algorithms.

Since Telefonica offers native CDN services, this prototype could help to manage them in a more effective manner.

Exploitation:

Telefónica is a Network Operator of almost global reach, offering data carrying services to content and services providers and even operating its own content distribution services. TID is involved in COMET through its Network Automatisation and Dynamisation Initative belonging to the TPI Unit (Transversal Projects and Innovation).

The prototype is intended to be exploited as a support system for Telefonica's content distribution services in the near future. The work to be done in the following months is to identify which (and how) would be the best means of deployment in the current CDNs operated by Telefonica and which extra requirements/features should be added to the prototype. With this aim in mind, meetings with the units in charge CDN management will be held to made them aware of the prototype advantages and obtain feedback, not only for the prototype but also for the ICN concepts

Decision will depend on the final assessment of COMET outcomes by the strategy department embedded in Telefonica TPI (Transversal Projects and Innovation).

Further research:

Supplementary parameters have to be included in the server health assessment algorithm as well as the possibility of mapping sets of servers to services, so that it is possible to issue collective queries which retrieve the health of a single service.

Socioeconomic impact:

Given the importance of server farms and load balancer in today's, any measure leading to better server health assessment will help to provide a better QoE for the final users.

For Telefonica, this sort of improvement would make its CDN services more attractive for the final users, attracting new subscribers.

6.6.3 Routing awareness prototype

Type:

Commercial exploitation of R&D results, Exploitation of R&D results via standards

Purpose:

Comparing to BGP, the routing awareness prototype provides path routing information among ISPs which is qualified with QoS parameters as provisioned. Moreover, it provides information about a number of alternative paths going towards particular destination domains (instead of a single path provided by BGP).

In such sense, it would help Telefonica to utilise the network links it manages in a more effective manner, saving bandwidth, energy and OPEX expenses, since most of these operations would be performed in an automatic/on the fly manner without resorting to external operators.

Exploitation:

Telefónica is a Network Operator of almost global reach, offering data carrying services to content and services providers and even operating its own content distribution services. TID is involved in COMET through its Network Automatisation and Dynamisation Initative belonging to the TPI Unit (Transversal Projects and Innovation).

The prototype is intended to be exploited as a support system for Telefonica's data distribution services in the near future. The work to be done in the following months is to identify which decision elements in Telefonica current network can do best use of the information supplied by this prototype and how and where this prototype should be deployed. To achieve this end, meetings with the units in charge of managing Telefonica's network will be held to made them aware of the prototype advantages and obtain feedback, not only for the prototype but also for the CCN concepts. Decision will depend on the final assessment of COMET outcomes by the Strategy Department embedded in Telefonica TPI.

From the research perspective, the prototype confirmed that designed multi-path and multi-criteria routing algorithms feasible for implementation and deployment in the multi-domain network. In this way, it confirmed that the shortest single path routing paradigm assumed in BGP protocol, which is commonly recognized as one of the fundamental limitations, could be relaxed in the future inter-domain routing protocols. However, it must be noted that the multipath routing protocol requires multipath transport capabilities supported by data plane mechanisms, e.g. as proposed stateless packet forwarding mechanism.

The obtained results could be exploited for contribution to: (1) IETF standardisation of new extensions to BGP protocol, (2) specification and design of new inter-domain protocol for the Future Internet. The IETF Inter Domain Routing (IDF) Work Group has recently started work on multipath BGP extension, which allows BGP peers to exchange information about multiple paths, but still BGP router has to select only one that is used for packet forwarding. Therefore, our results could be exploited for further BGP extensions that enable BGP router establishing multiple paths in end-to-end scenario. On the other hand, the prototype results could be directly exploited in the research on inter-domain routing for the Future Internet. In particular, the multi-criteria and multi-path features could be exploited in research on the SDN (Software Defined Networks). WUT will exploit prototype in research on controller entity for SDN network.

Further research:

The Routing Awareness prototype should be extended in order to provide information about real time conditions. Moreover, the important research direction is integration of multipath routing with the existing network technologies, e.g. IP/MPLS, and emerging network technologies, e.g. SND.

Socioeconomic impact:

Any system which can provide QoS information about possible routes to be taken when transmitting contents is of great interests for users and content providers, since it would enable upper entities to adopt the right measures and decisions which enable them to ensure QoE for end user services.

In such sense, Telefónica could adopt a more competitive position in comparison to other network operators, by offering a better quality either for the user of its own content distribution services or for the content providers which have chosen Telefónica as its ISP.

6.7 Testbed

6.7.1 ICN testbed

Type:

General advancement of knowledge

Purpose:

The COMET project designed and deployed the fully operational ICN testbed that consists of three local sites located at partner premises, i.e., Madrid/TID, Limassol/PTL and Warsaw/WUT. This testbed allows demonstrating ICN functionalities and performing experiments with the prototype running in network environment.

Exploitation:

WUT, as an academic partner, exploits the ICN testbed (at least the WUT local site) as the experimental facility for future research and education activities. In the education area, the ICN testbed will be used to: (1) demonstrate students the ICN concept and its main functionalities, (2) update courses, e.g. “Fundamentals of Future Internet”, with new hands-on labs and define students’ projects focused on ICN experiments, and (3) offer the ICN experimental environment for MSc projects and PhD studies. In the research area, the ICN testbed will be exploited for further research on topics studied in COMET and for new research directions. In particular, the ICN system scalability, multi-path routing algorithms, and stateless packet forwarding mechanism would be further investigated. Moreover, the WUT testbed would be exploited as the experimental facility for our future projects.

Further Research:

Currently, the ICN testbed consists of five domains so experiments can be performed only in a limited scale. Therefore, WUT will investigate how to federate the ICN testbed with other experimentation facilities. We consider possibility to network ICN testbed with PL-LAB - polish research and experimentation infrastructure developed by Future Internet Engineering project.

Further research and experimentation based on ICN testbed will focus on the prototype extension to support content chunking (MPEG DASH), video adaptation, user mobility, content caching and multicasting.

Socioeconomic Impact:

The ICN testbed has impact on WUT academic and research activities. First of all, it gives new research and experimentation opportunities for WUT researchers and students (including PhD students). An additional impact is a promotion of ICN concept in academic society. Moreover, the impact would be increased once the ICN testbed would be connected with the PL-LAB.

7 Summary and Conclusions

This deliverable is the final document of the COMET project, presenting its key assets and results as well as partners' future plans and methodology to exploit them.

Two approaches have been specified, implemented, simulated and tested; the **decoupled** approach which follows the current Internet paradigm, where content resolution is similar to DNS and decoupled from the content delivery, and the **coupled** approach, which is a more revolutionary content-centric approach, in which the content resolution is tightly coupled to the content consumption. For each approach, the following algorithms and mechanisms were specified and implemented: **Gossip-based content resolution** and **In-network caching mechanisms** (coupled), **Multi-criteria server and path selection**, **Multi-path and multi-criteria routing** and **Stateless packet forwarding mechanisms** (decoupled).

The following two models were designed: **In-network caching model** and **ICN evaluation method**, aiming to evaluate the performance and scalability of content caching systems and ICN solutions in general. In addition, **ICN simulators** were developed by the academic partners, to simulate both approaches' mechanisms and prove their feasibility in Internet scale.

To test and demonstrate the decoupled approach, several components were implemented and integrated: the **ICN controller and forwarding prototype**, which is the controlling module in the CMP and configures the network elements in CFP, the **Server and network monitoring prototype**, used to monitor server and network conditions and the **Routing awareness prototype**, which provides the available routes, enhanced with required QoS metrics. In addition, an **ICN testbed** was designed and created between 3 partners, used for demonstration and performance testing purposes.

The two main contributions and results of the project were the proof of **ICN feasibility at Internet scale** and the **"Cache less for more" recommendation**. Simulation results and tests performed in the federated testbed proved that the COMET solution is feasible at Internet scale and could be deployed by Internet stakeholders, while the latter is the key outcome of research work performed in the project, specifying two different approaches for in-network caching, improving networks' efficiency.

All abovementioned results were disseminated and demonstrated in high-quality conferences, magazines and events during the 3 years of the project. 24 scientific papers were accepted and presented in high-tier conferences and magazines, receiving multiple citations and scientific interest. The consortium was also active in concertation activities with related research projects in the ICN field, organized 3 workshops to highlight its results and impact, demonstrated its prototypes and also contributed to relevant standardization bodies and WGs.

COMET's exploitation strategy will consist of measures and plans of 3 types: **General advancement of knowledge**, **Commercial exploitation of R&D results**, and **Exploitation of R&D results via standards**:

- The industrial partners of the COMET consortium will mainly focus on the commercialization of the implemented prototypes (controlling and forwarding, server and network monitoring and routing awareness prototype). Market and engineering work is currently performed to investigate the potential for deployment to their networks or integration to their existing portfolio solutions for particular modules of the prototype. The potential adoption of COMET system from Internet stakeholders would certainly improve content delivery services' QoS and content consumers' QoE, while it seems likely that new market opportunities would arise, resulting in potential economic gains for the involved partners and new employment jobs to support these services.
- The academic partners of the COMET project will offer new MScs and PhDs theses so as to continue their research in the ICN field, while existing courses will be updated or new courses will be introduced to their course catalogue, to contribute to the advancement in knowledge of the education community. Hence, more researchers would become familiar to

the concepts of the ICN and would be interested to participate in ongoing and future research in that area, by extending and improving specified algorithms, and mechanisms.

- Finally, the COMET consortium will continue to contribute to relevant standardization bodies, related to ICN research (e.g. IRTF ICNRG), and BGP extension (e.g. IETF IDF), aiming to increase the project's impact to industrial sector and scientific community.

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9 Abbreviations

BGP	Border Gateway Protocol
CACF	Content-Aware Caching Functional block
CAFE	Content-Aware Forwarding Entity
CAFF	Content-Aware Forwarding Functional block
CAIDA	Cooperative Association for Internet Data Analysis
CAN	Controller Area Network
CDN	Content Distribution Network
CFP	Control Forwarding Plane
CME	Content Mediation Entity
CMF	Content Mediation Functional block
CMP	Control Mediation Plane
CRE	Content Resolution Entity
CRF	Content Resolution Functional block
CRMF	Content Resolution and Mediation Entity
COMET	COntent Mediator architecture for content-aware nETworks
DHT	Distributed Hash Table
DNS	Domain Name System
ICN	Information Centric Networking
IPTV	Internet Protocol Television
ISP	Internet Service Provider
MCDA	Multiple Criteria Decision Analysis
MPLS	MultiProtocol Label Switching
MSc	Master of Science
NDN	Named Data Networking
NLRI	Network Layer Reachability Information
NSP	Network Service Provider
PhD	Doctor of Philosophy
PMF	Path Management Functional block
P2P	Peer-to-peer
PoC	Proof of Concept
QoE	Quality of Experience
QoS	Quality of Service
RAE	Routing Awareness Entity
SDN	Software Defined Networking
SNME	Server and Network Monitoring Entity

SNMF	Server and Network Monitoring Functional block
STREP	Specific Targeted Research Project
SWOT	Strengths, Weaknesses, Opportunities and Threats
VLNSP	Very Lightweight Network and Service Platform
VoD	Video on Demand
WG	Working Group

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