P2P Middleware for Extending the Reach, Scale and Functionality of Content Delivery Networks

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Abstract

The contribution of this paper is a novel peer-to-peer (P2P) middleware solution for extending the reach, scale and functionality of content delivery networks (CDNs). The research problem of extending legacy CDN functionality towards user-to-user content networking and enhancing the CDN quality attributes of reach and scale are addressed. The proposed P2P middleware solution extends the reach and scale of CDNs to cover the digital home environment via specialized virtual multimedia home gateways and extends the legacy CDN functionality by enabling user-generated content sharing via the P2P extended CDN infrastructure.

1. Introduction

The content delivery networks (CDNs) are specialized networks deployed for delivering content from the place of publication closer to the content consumers. Because of CDNs, the content providers do not have to maintain a content delivery infrastructure and can outsource the content delivery to CDN providers [1]. A well-known example of a CDN is Akamai [2], with over ten thousand edge servers deployed in over one thousand networks in over sixty countries. Two important quality attributes for a CDN are scale and reach [1], which can be used for defining the value of a CDN. The scale refers to size of the aggregated CDN infrastructure and the reach refers to the increasing diversity of content locations.

While CDNs traditionally provide unidirectional content delivery from the professional content providers towards the end users, there is a growing demand for services that deliver and share the content from one end user to another; the amount of digital content produced by the users is increasing due to personal recordings made using various in-home and mobile devices, and the users want to share their content with other users (e.g. with family, friends and user groups), as indicated by the recent popularity of, e.g. the YouTube [3] video sharing service, which lets users upload, view, and share video clips. There are many examples in the area of peer-to-peer (P2P) applications, such as Napster, Gnutella-based file-sharing programs like Kazaa and BearShare, the FreeNet, etc., which enable individual consumers to act as content providers. However, they have been applied to illegal distribution of content without appropriate digital rights. The aim of the research presented in this paper has been to apply the P2P technologies within a legal context and trusted networks to improve the capabilities and functionality of legacy CDNs.

In contrast to client-server architectures that are often applied to content delivery applications, the advantages of P2P architectures include enhanced load balancing, dynamic information repositories, better fault tolerance and availability due to distribution of functionality, content-based addressing and improved searches [4]. On other hand, the pure P2P architectures lack efficient centralized control, trust and integration with legacy systems, making hybrid P2P architectures an appealing approach [5]. The lack of general-purpose P2P middleware, leading to development of proprietary P2P applications, has been acknowledged in the literature [5]. The most well known general purpose P2P middleware effort is JXTA [6], which does not limit its functionality to any specific application domain but provides generic P2P communication services facilitating P2P application development.

The research presented in this paper contributes to the work on generic P2P middleware and its application for content delivery in trusted networks with a hybrid P2P architecture approach contributing a solution that can be integrated with legacy CDNs. This paper differs from the existing literature by taking a unique approach to the research problem of extending

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the reach and functionality of legacy CDNs. The solution presented here contributes to filling the existing gap between the research on middleware [7], P2P technology [4, 6, 8] and content delivery networks [9-11] by proposing a P2P middleware-based solution for extending the reach and scale of CDNs to cover the digital home environment and enhancing the traditional CDN functionality by enabling user-generated content sharing amongst end users.

The work presented in this paper provides proof of the implementation of the concept presented in [12] and contributes to the integrated P2P middleware architecture and main functionalities complementing the previous work. The P2P middleware applied to content location discovery as part of a CDN request routing system has previously been presented in [13]. A middleware platform architecture accommodating the proposed P2P middleware solution for enabling P2P messaging of gateway-based applications has been published in [14].

The requirements of end user-generated content sharing posed for future content delivery systems are taken into account; the architecture of the proposed solution allows users to participate in P2P content delivery via a specialized gateway referred to as the Virtual Multimedia Home (VMH) gateway. The gateway approach is in line with the recent developments on home gateways for the digital home environment [14-16] and is envisioned to be deployable as part of a broadband-connected home gateway or media centre PC in the home environment. The VMH gateways have a central role in the proposed solution, enabling the P2P extensions and enhancements to be introduced into CDNs, as well as enabling user-to-user content sharing.

The rest of the paper is organized as follows; Section 2 presents the system architecture covered by the P2P middleware solution, Section 3 contributes the P2P middleware architecture that has been functionally validated in a series of prototype implementations overviewed in Section 4, and Section 5 concludes the paper.

2. System Architecture

The system architecture and deployment of the proposed P2P middleware solution is overviewed to give an insight into the role of the P2P middleware in extending the functionality, reach and scale of CDNs. The P2P middleware architecture consists of three different subcomponents; Peer Communication Service (PCS), P2PSearchMiddleware and P2PExtensionMiddleware, which will be covered in Section 3 in more detail.

The system architecture consists of edge servers of a CDN located within the CDN domain, special gateways that are referred to as VMH gateways located at the CDN customer domain, and, finally, the terminals used for accessing content either via the VMH gateways or directly from the CDN. In addition to just providing access to content, the VMH gateways are able to execute application services (e.g. for sharing user-generated content with other users or for instant multimedia messaging) that utilize the underlying P2P middleware and overlay network in their operation. From the CDN viewpoint, the VMH gateways provide additional content replica storages into the CDN, and from the end user viewpoint, they provide application services for distributing and sharing user-generated content.

The P2P middleware solution is deployed into the edge servers of a CDN, connecting them with a P2P overlay network and realizing the first P2P extension (P2P Ext #1 in Figure 1) with regard to legacy CDNs. This deployment of the P2P middleware includes the Peer Communication Service (PCS) providing the generic services related to the P2P overlay network communications and management, and the P2PSearchMiddleware providing the search functions for content location searches within the CDN. The P2PSearchMiddleware is designed to be integrated with the CDN request routing system, also known as the client redirection mechanism [9]. The P2PSearchMiddleware can be applied to enhance the quality of legacy CDNs as it enables better fault tolerance and availability via distribution of the CDN edge server search and indexing functions.

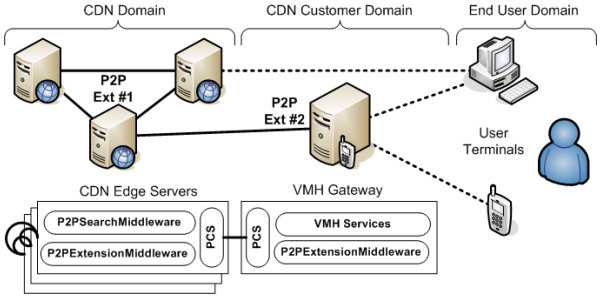

Figure 1. System and P2P middleware solution architecture.

The P2PSearchMiddleware provides a scalable and distributed content location search functionality that can be applied as part of the CDN request routing system and is capable of handling the content indexing within a CDN in a distributed and scalable fashion. Central knowledge of content replica locations within

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the CDN is not assumed by the P2PSearchMiddleware but available content replica locations can be searched via the P2P overlay network in a distributed fashion at the time of incoming content retrieval requests. More detailed information on integration of the P2PSearchMiddleware with a CDN request routing system can be found in [13].

The P2P middleware solution also includes another P2P extension that is realized by harnessing the VMH gateways as part of the content distribution infrastructure. In our solution this is done by deploying the P2PExtensionMiddleware and PCS to the VMH gateways in addition to the CDN edge servers (P2P Ext #2 in Figure 1). The P2PExtensionMiddleware creates an extension to a CDN and uses the generic P2P communication services provided by the PCS. In this deployment the P2PExtensionMiddleware instance at the CDN edge server has a super-peer role hosting all the instances at the VMH gateway member nodes of the P2P extension network. Each P2P extension consists of one edge server and one to many VMH gateways that host the P2PExtensionMiddleware software.

Figure 1 illustrates the described system architecture and the deployment of the P2P middleware solution in it. Enabled by the P2P middleware, both presented P2P extensions, illustrated in Figure 1, enhance the quality of a CDN by contributing to the scale and reach of the CDN. The scale of the CDN, referring to the size of the aggregated CDN infrastructure, is enhanced by harnessing the VMH Gateways to become part of the content distribution and delivery infrastructure. The reach of the CDN, referring to the increased diversity of the content locations, is enhanced by connecting the CDN edge servers with each other and the VMH gateways, increasing the diversity of possible content location when compared to legacy CDNs.

As illustrated in Figure 1, P2P middleware may be applied to extend the reach and scale of CDNs to cover the digital home environment via VMH gateways and to extend the traditional CDN functionality by enabling user-generated content sharing amongst end users via the CDN P2P overlay infrastructure.

3. Middleware Architecture

The P2P middleware consists of three different subcomponents: Peer Communication Service (PCS), P2PSearchMiddleware and P2PExtensionMiddleware. Figure 2 illustrates the overall architecture of the P2P middleware and the main functionalities of its subcomponents. The PCS component provides the generic services related to P2P overlay network management and communication in a service-oriented and easy-to-use fashion. The P2PSearchMiddleware component utilizes the services of the PCS and adds services for distributed content location searches, content indexing, CDN composition and CDN management within the whole CDN. The P2PExtensionMiddleware also relies on the services provided by PCS and enables extension of the CDNs with dynamic P2P extensions in the CDN customer domain. The functionality of the P2PExtensionMiddleware includes P2P extension network management, content indexing and content location searches in the P2P extension network, and, finally, content distribution into the P2P extension network.

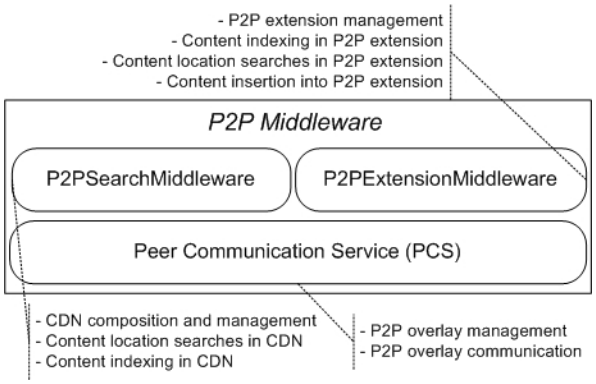

Figure 2. P2P middleware architecture.

3.1 Peer Communication Service (PCS)

The PCS subcomponent of the P2P middleware provides the generic services utilized by the other P2P middleware components. The PCS provides management and communication services to its applications within the P2P overlay network it establishes. The overlay network may consist of PCS instances running at any Internet-connected nodes. The main service the PCS provides is message exchange amongst its applications. In addition, the PCS provides management services for finding and advertising P2P applications and peers or application and peer groups within the overlay network. The management services provided by the PCS include creation of new application and peer groups with restricted access policies, and providing an authentication and authorization mechanism for joining these groups. The messaging between the applications is supported in both a one-to-one and a one-to-many fashion, enabling also group communication. The PCS utilizes application identifier-based addressing in communications, enabling it to connect to the network

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from different physical locations after the connection of one session is closed while still preserving the same appearance in the P2P overlay network. The PCS provides its services in a service-oriented and easy-to-use fashion, facilitating the application development. The service functionality the PCS provides for its applications is summarized and illustrated in Figure 3.

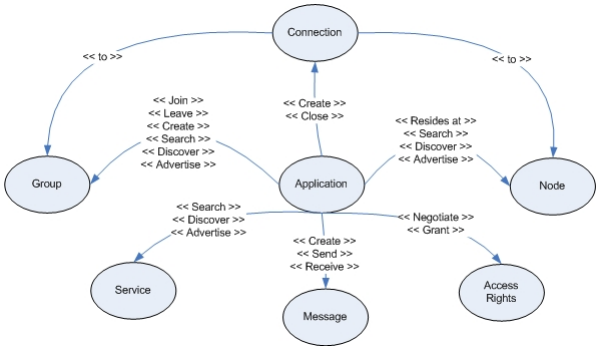

Figure 3. PCS services and functionality.

3.2 P2PSearchMiddleware

The P2PSearchMiddleware enables conducting distributed searches within the P2P overlay network established by PCS. The searches are based on applying a P2P grouping of the content hosting nodes, such as CDN edge servers. The P2PSearchMiddleware has been especially designed for the needs of CDNs, whereas the P2P middleware solution presented in this paper implements the first level of CDN P2P extension, connecting the edge servers of the CDN with a P2P network by deploying the P2PSearchMiddleware and PCS instance on each CDN edge server. This improves the availability of a CDN via redundancy, enables the creation of P2P-based load-balancing mechanisms and provides improved fully distributed but scalable searches within the whole CDN. The P2PSearchMiddleware also enables composition of a CDN in a dynamic and scalable fashion utilizing the P2P grouping of edge servers. The P2P grouping of edge servers is applied to achieve efficient and scalable searches in the CDN via a hierarchical structured P2P network approach. The P2PSearchMiddleware provides searches covering the edge server neighbourhood or the whole CDN. The P2P grouping organization utilized for constructing the CDN and conducting distributed searches is illustrated in Figure 4.

The P2PSearchMiddleware operates in a structured hierarchical P2P overlay network, as illustrated in Figure 4. The CDN edge servers may have two different roles in the P2P overlay: *normal* and *listener*. The edge server operating in a *normal* role is not actively listening or replying to requests that are made in the CDN group, which is the first level of the hierarchical grouping applied in the solution. In the CDN group, only the edge servers having the *listener* role are actively listening and replying to the requests made in the group. The edge servers that have the listener role represent their edge server neighbourhood in the CDN group, lowering the network traffic generated by the content location searches made within the whole CDN.

The second level in the P2P grouping hierarchy is the neighbourhoods, consisting of CDN edge servers that are in close proximity to each other from the network and/or geographical point of view. The neighbourhoods consist of edge servers having the normal role and at least one edge server having the listener role. The edge server in the listener role is responsible for content indexing and content location search replies on behalf of its neighbourhood within the CDN group. The searches covering only the neighbourhood are propagated as group messages within the size-limited neighbourhoods. The searches covering the whole CDN are made within the CDN group. Accordingly, the edge servers having a normal role serve the search requests within the neighbourhood groups and the edge servers having the listener role serve the search requests in the CDN group. In order to provide better fault tolerance and availability, the listener roles should be autonomously managed and dynamically assigned within the neighbourhoods.

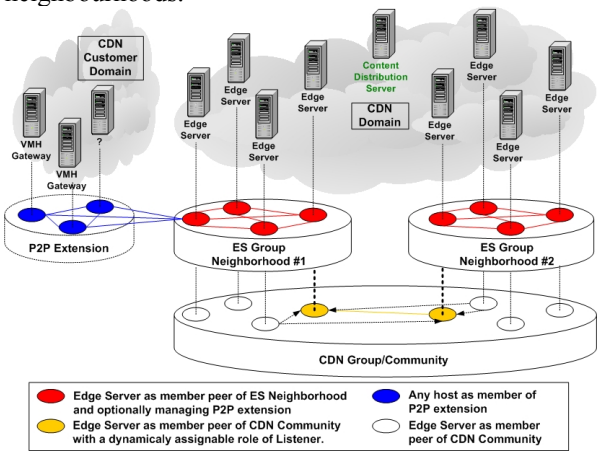

Figure 4. P2P grouping within a CDN.

The P2PsearchMiddleware, together with the PCS, has been utilized in implementing content location discovery within asynchronous broadcast type content delivery networks. More details can be found in [13].

3.3. P2PExtensionMiddleware

The P2PExtensionMiddleware is the subcomponent of the P2P middleware enabling dynamic extensions to the CDN infrastructure. Any Internet-connected node having available storage space may be considered a member node for the CDN's P2P extension at the CDN customer domain. The P2PExtensionMiddleware realizes the second level of P2P extensions to star topology CDNs, extending the reach and scale of the CDN. It provides CDN quality enhancements such as enabling better load balancing by enabling content replicas to be placed even closer to the end user. It also enhances the CDN's content availability by providing additional dynamic content repositories and parallel downloads on the "last-mile" of content delivery to increase the content delivery performance.

The P2PExtensionMiddleware is designed to be deployed at CDN edge servers and the VMH gateways. Regarding the deployment of the P2PExtensionMiddleware, each CDN edge server instance of P2PExtensionMiddleware establishes and manages independent P2P extensions, as illustrated in Figure 4. The P2P extension network is established as an access-controlled P2P group utilizing the services provided by the PCS. The additional P2P extension member nodes executing P2PExtensionMiddleware, such as VMH gateways, may join the CDN extension by contacting the P2P extension-managing CDN edge server and providing appropriate authentication credentials. The management of authentication credentials is not handled by the P2P middleware; a separate credential management system is required. For distribution of encrypted content, the P2P extension members do not necessarily have to be trusted by the CDN provider; for distribution of unencrypted content, the solution supports restricted membership P2P extensions with authentication and authorization of member nodes for building the trust relationships.

The P2PExtensionMiddleware utilizes services provided by the PCS for basic P2P communications and is able to implement the P2P extensions in a CDN as either a public or restricted membership P2P group. The services provided by the P2PExtensionMiddleware include P2P extension establishment and management, content distribution, content indexing, content searches and parallel content downloads within the extension.

At the conceptual level, the P2P extensions of CDNs are well in line, or even symbiotic, with the concept of Virtual Multimedia Home (VMH). In the VMH concept, the VMH gateways have P2PExtensionMiddleware deployed, making the gateways part of the CDN's dynamic extension infrastructure providing additional content replica locations for content distribution. In addition, the VMH gateways provide CDN providers or any third-party service provider with a target environment for P2P service execution.

From the CDN point of view, the VMH gateways act as additional storages for CDN content. A CDN edge server hosting a P2P extension can divide the content into smaller pieces and further distribute it to the VMH gateways' storages available in the P2P extension. Dividing and distributing the content into the VMH gateways enables the P2PExtensionMiddleware to download the content from multiple sources in parallel, speeding up the content delivery and reducing the load at a single P2P extension node. The P2PExtensionMiddleware's support for parallel downloads also addresses the problem of asynchronous broadband access networks (e.g. ADSL) by enabling fast downloads originating from multiple sources. The use of multiple parallel content sources lowers the upload bandwidth requirements of an individual content-providing P2P extension node.

From the end user point of view, the VMH gateways hosting the P2PExtensionMidldeware act as access points to the P2P network. End users can distribute and share personal content with other users of the CDN and also access their shared content via applications based on the P2PExtensionMiddleware and running at the VMH gateway. Authenticated and authorized CDN customers can also access CDN content via the VMH gateways.

When content is inserted into the P2P extension, it is divided into smaller pieces and copies of the pieces are further distributed to the VMH gateways. The content index of the P2P extension hosting the edge server contains the information needed for merging the content back together, and the locations of each piece of the content distributed within the P2P extension.

User-generated content and CDN content is indexed separately by the P2PExtensionMiddleware and VMH gateway users have no direct access to individual pieces of CDN content located at the VMH gateways. Within the P2P extension, the CDN content can only be accessed by making a direct search request to the extension-hosting edge server. Even if the content could be retrieved from multiple sources in parallel, it would appear as though it had come directly from the contacted edge server. Accordingly, the content chopping, distribution and merging done within the P2P extension is made completely transparent to applications by the P2PExtensionMiddleware.

Enabled by the P2PExtensionMiddleware, the applications may search user-generated content by making group queries to the P2P extensions of the CDN, and the content is transferred directly from one extension member to another. Separate indexing and management of user-generated and CDN content provided by the P2PExtensionMiddleware makes it possible to keep the CDN content from mixing together with the user-generated content yet still use the same underlying P2P network infrastructure.

4. Functional Validation

The P2P middleware architecture presented in Section 3 has been implemented and functionally validated in 3 prototype implementations. Each prototype implementation functionally validates specific parts of the presented P2P middleware architecture for extending the reach, scale and functionality of content delivery networks. The prototype implementations are briefly overviewed in this section.

4.1. Peer Communication Service Prototype

The PCS prototype was implemented by applying JXTA technology [6]. The JXTA release used was version 2.3.1 for Java 2 SE. The PCS was implemented using Java 2 SE in such a way that JXTA 2.3.1 was completely encapsulated within the PCS component and the P2P services and functionalities were provided via the easy-to-use service-oriented interface illustrated in Figure 3. The PCS encapsulation limits the possibility of changes caused by the Project JXTA open source project being reflected in the PCS applications, but only within the PCS implementation. The PCS was validated with a prototype implementation of an instant messaging application that utilizes the PCS services. This application enabled user-to-user and user-to-group messaging with messages including text as well as digital pictures. Furthermore, both the P2PSearchMiddleware and the P2PExtensionMiddleware utilize PCS for basic P2P operations; thereby, the prototypes presented in this paper functionally validate the PCS.

4.2. P2PSearchMiddleware Prototype

The P2PSearchMiddleware was validated in a prototype implementation enabling search functions for content locations in the P2P overlay network. The P2PSearchMiddleware utilized the PCS for the P2P overlay network formation and provided the search functions for the established and structured P2P overlay network. The implemented P2PSearchMiddleware provided two kinds of functions for content location searches in the network. The first search function limited the search to the same edge server neighbourhood. The use case sequences for the neighbourhood search, identified in Figure 5, were:

1. Search function for content location in the neighbourhood called. Attributes identifying the content, defining the required number of results and the available search time are given for specifying the search.

1.1. Search request is propagated to the edge servers in the same neighbourhood.

1.2. The edge servers hosting the content respond with the content locations.

1.3. When reaching the given time limit or having found the required number of results, the results are returned to the application.

Another use case, also presented in Figure, 5 described the search function of the content locations for the whole CDN. The use case sequences for the CDN search, identified in Figure 5, were:

2. Search function for content location in CDN called. Attributes given as for the neighbourhood search.

2.1. The search is only propagated to the edge servers operating as *listeners* in the CDN.

2.2. The listeners search local databases and forward the search to the edge servers hosting the content.

2.3. The edge servers hosting the content respond with the content locations.

2.4. When reaching the given time limit or having found the required number of results, the results of the search are returned to the application.

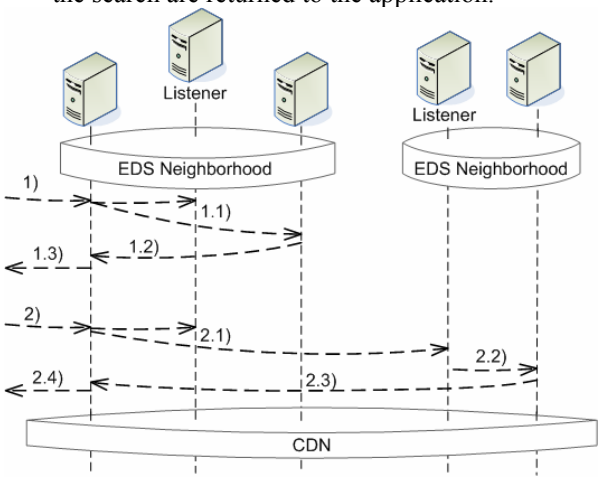

Figure 5. Searching content locations with P2PSearchMiddleware.

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4.3 P2PExtensionMiddleware Prototype

The validating use cases of the P2PExtensionMiddleware prototype included: Content insertion to the P2P extension, Content location search and download within the P2P extension, and end user content sharing. The validating use cases marked in Figure 5 are described in order to demonstrate the P2PExtensionMiddleware functionalities:

1. Content insertion into P2P extension: The CDN content is inserted into the P2P extension from the edge server running a P2PExtensionMiddleware instance. In the demonstration this was done manually via a GUI. In actual deployments this step could be done automatically by the edge server software (e.g. controlled by load-balancing algorithms)

1.1 Content indexing: The content that is inserted into the P2P extension is indexed at the edge server instance of the P2PExtensionMiddleware

1.2 Content distribution: The content that is inserted into the P2P extension is chopped into smaller pieces and the individual pieces are distributed to the VMH gateways that are member nodes of the P2P extension. The individual content piece locations are updated to the P2P extension content index hosted by the edge server.

2. Content location searches and download within P2P extension: The CDN content that is inserted into the P2P extension is searched via the edge server instance of the P2PExtenisonMiddleware. The searches are made in the content index of the P2P extension.

2.1 Resolving piece locations: The locations of the content pieces residing in the P2P extension are resolved based on the content index of the P2P extension.

2.2 Piece download: Any VMH gateway running the P2PExtenisonMiddleware is able to download the content consisting of individual content pieces in parallel from multiple different locations within the P2P extension.

2.3 Content merging: The VMH gateway running the P2PExtenisonMiddleware merges the content consisting of downloaded content pieces.

3 End user content sharing: The VMH gateway executes an application that utilizes the underlying P2P overlay network for enabling the sharing of end user-generated content via the VMH gateways that are members of the P2P extension. First, the end user-generated content is inserted into the VMH gateway from a mobile device.

3.1 End user content indexing: The end user content inserted into the VMH gateway is indexed by the local instance of the P2PExtensionMiddleware.

3.2 End user content search: The searches of the end user content within the P2P extension are made by propagating the search request as a group message within the P2P extension. The P2PExtensionMiddleware instance of the VMH gateway hosting the content being searched will reply to the search request with a one-to-one message.

3.3 End user content delivery: Based on the search reply received in step 3.2, the located end user content can be directly retrieved from the VMH gateway hosting the content.

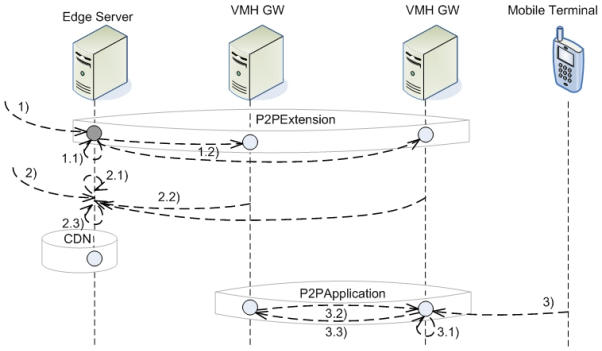

Figure 6. P2PExtensionMiddleware prototype configuration and validating trial use cases.

The overviewed prototype implementations and use cases functionally validated the P2P middleware architecture and all its subcomponents.

5. Conclusion

The presented work contributes a novel P2P middleware solution and architecture for extending the reach, scale and functionality of legacy CDNs. The solution was functionally validated in a series of laboratory prototype implementations overviewed in the paper, and successfully applies P2P technologies in a trusted and legal way to enable improvement of the load balancing, scalability and fault tolerance of legacy CDNs.

The presented P2P middleware solution extends the reach and scale of CDNs to cover the digital home environment via special gateways, referred to as Virtual Multimedia Home (VMH) gateways, which host P2P middleware establishing P2P extensions to CDNs. The P2P extensions to a CDN enable content replicas to be further distributed within the P2P

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extension networks, increasing the diversity of possible content locations within the CDN. The presented P2P middleware solution also extends the functionality of CDNs towards enabling user-generated content sharing; user-generated content sharing applications executed at the VMH gateways can utilize the P2P extended CDN infrastructure enabled and mediated by the P2P middleware.

The presented P2P middleware solution has been integrated, demonstrated and validated as part of a novel CDN architecture, referred to as mCDN architecture [17]. The integration of VMH gateway functionality as part of a home gateway is being researched in an ongoing project [18].

6. Acknowledgment

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