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Experimenting with Services over an Information-Centric Integrated Satellite-Terrestrial Network

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Abstract: The recent paradigm shift in the Internet's usage, from the host-centric to a content-centric communication model, where users request information irrespectively of its location, is coupled with an increasing need for converged and seamless access over heterogeneous wired and wireless networks. By integrating satellite communication components into a publish-subscribe Information-Centric Networking (ICN) architecture, we jointly exploit the capabilities and advantages of each: transparent use of terrestrial multicasting and satellite broadcasting, content-based traffic engineering, multipath transfer, in-network caching capabilities, and seamless mobility. Experimenting over a realized integrated-terrestrial ICN testbed, we demonstrate and illustrate key functionalities and gains for various services and applications.

Keywords: Information-Centric Networking, Satellite Communications

1. Introduction

The Internet's current usage is content-centric; the focus is not anymore on connecting end-hosts but on efficient content dissemination and retrieval transparently to the network access technology. In an effort to introduce content-awareness for more efficient control and delivery over content flows, various patches to the Internet's architecture have emerged (e.g. CDNs, proxies, Deep Packet Inspection) which have progressively led to the ossification of the Internet. To address these changes in Internet usage, the idea of redesigning the Internet based on the Information-Centric Networking (ICN) paradigm has radically emerged. Explicitly routing on content identifiers, native support for mobility and multicasting, and multi-source multi-path transfer are key ICN features that can bring the desired efficiency in content retrieval and dissemination over heterogeneous networks. At the same time, satellite technologies are long being exploited for wide area content broadcasting, while their potential is high for critical Future Internet application fields, such as Machine-to-Machine (M2M) services, and in geographic areas where terrestrial networks do not exist and are very costly to deploy.

Along these lines, this work aims to illustrate the gains of using a publish/subscribe-based ICN architecture for integrating terrestrial and satellite networks [1], jointly exploiting the advantages of each technology: Transparent use of terrestrial ICN multicasting and satellite broadcasting, native content-based traffic engineering by routers, multipath transfer (which allows bandwidth aggregation and offers resilience to link failures or to disconnections from one access network (for multihomed devices)), in-network caching support, and seamless mobility. The first three are necessary to efficiently utilize network resources and provide robustness to failures, which is particularly important when the network consists of heterogeneous wired/wireless technologies with different capacities, costs and coverage, such as terrestrial and satellite links. In-network caching can assist in improved content delivery performance and more efficient use of satellite resources, while seamless mobility support is necessary for both horizontal and vertical handovers.

Our design is based on PSI (Publish-Subscribe Internet), a Future Internet ICN architecture defined by the PURSUIT project [2]. PSI follows a publish-subscribe communication model, aiming to decouple (i) data/service provision from its location, (ii) name resolution from data transfer, and (iii) routing and topology management from forwarding [3]. It enables content-based path selection and facilitates multipath transfer, native multicast and mobility support. PSI's design builds on the separation of three core functions: Rendezvous, Topology Management, and Forwarding (RTF). The Rendezvous function involves matching publications with subscriptions and initiates routing, forwarding and distribution decisions. The Topology Management (TM) function monitors network topology, detects changes and creates information delivery structures putting in effect policies and specific dissemination strategies. Finally, the Forwarding function implements information forwarding using LIPSIN [4]: Each link is assigned a forwarding identifier (FId) and the TM builds a delivery tree which includes such FIds. FIds are encoded in a Bloom filter placed in the header of each individual packet and used for forwarding decisions.

The paper is structured as follows: Section 2 presents our testbed, which integrates satellite and terrestrial Information-Centric Networks. In Section 3, we demonstrate key functionalities of our architecture along with results from testbed experiments, before we conclude our work in Section 4.

2. An integrated testbed

The testbed used for building ICN functionality into an integrated satellite-terrestrial networking environment (Figure 1) includes nodes running Blackadder [5], which is an open-source prototype PSI implementation, and also emulated satellite components using the OpenSAND [6] open-source satellite network emulator. The features of our testbed are described in this section.

2.1 An Information-Centric Networking prototype

Blackadder implements the RTF functionality and is based on the Click modular router framework [7]. Blackadder runs in Linux and can operate either in user space or in kernel space offering two modes of operation: It can either communicate through the exchange of raw Ethernet frames over a LAN or operate in overlay mode on top of IP. For reasons of ease of deployment and due to testbed constraints, we operate Blackadder in overlay mode.

Blackadder exposes a publish/subscribe API to facilitate application development. The video streaming and file transfer applications, as well as the transport layer services we implemented (see Section 2.3) are built using this API.

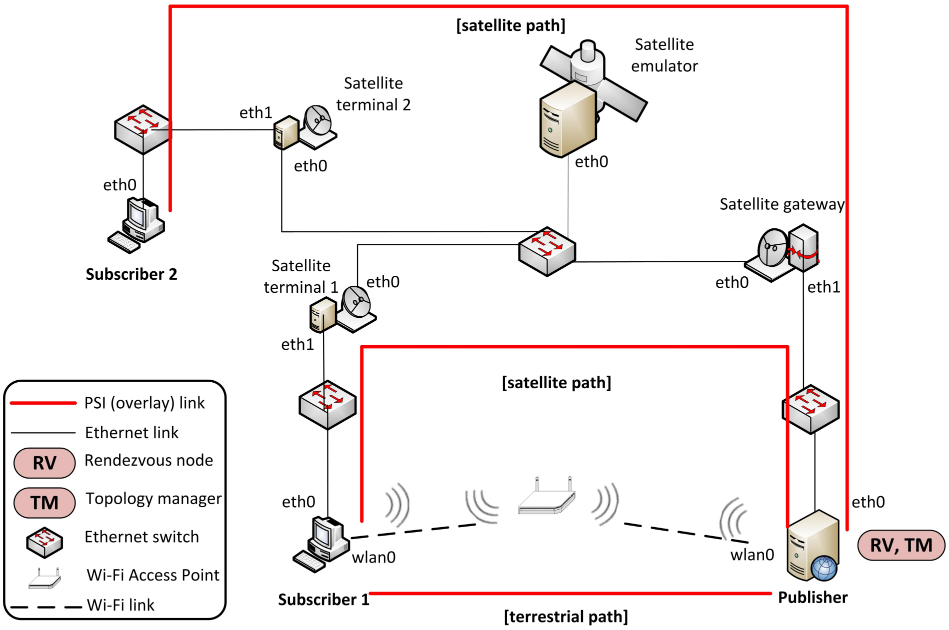

Figure 1: Testbed topology

2.2 *Satellite network emulation*

We emulate satellite links using OpenSAND, a tool which implements real satellite DVB encapsulation, such as Generic Stream Encapsulation (GSE) [8], Unidirectional Lightweight Encapsulation (ULE) [9], or ATM Adaptation Layer 5 (AAL5), and emulates lower layer protocols, such as MPEG-2 Transport Streams (MPEG-2 TS) or ATM. It supports three types of nodes: Satellite Terminal (ST), Satellite Emulator (SE), and Gateway (GW). STs transmit/receive traffic to/from the emulated satellite. The SE emulates a transparent or regenerative satellite link including adding a preconfigured propagation delay. Finally, the GW acts as the central access point for STs and as the satellite NCC (Network Control Center), which monitors and controls the satellite network, and performs real-time time/frequency resource allocation. The performance of the emulator is bound to the hardware platforms used. Typically, it should be able to achieve more than 15 Mbps on the downlink and 5 Mpbs on the return link. We can also emulate satellite link unavailability to evaluate performance in the face of short-term link loss due to, e.g., attenuation owing to environmental conditions or loss of line-of-sight when a mobile satellite terminal enters a tunnel. OpenSAND runs in Linux, which facilitates its integration with Blackadder.

2.3 *Transport services*

We have implemented an application layer transport protocol based on the Blackadder pub/sub API. Our protocol's most innovative characteristics are that it allows multipath and multisource file transmission and that it is receiver driven. It exploits PSIs centralized path selection requiring an efficient Topology Manager (TM) capable of (a) finding k-shortest paths among two nodes and (b) constructing a pair of FId-reverseFId for each path. The FIds are transmitted to the subscriber (receiver), which uses them to explicitly request data-chunks via a single or via multiple paths from each available publisher (sender). Therefore, each file is fragmented into fixed size data chunks and the protocol utilizes a pull model. According to this model, the subscriber manages the service by distributing chunk requests among available paths. The simultaneous content transmission via multiple paths increases the protocol's robustness to node failures and brings performance benefits due to bandwidth aggregation. Also, compared to single path protocols which may suffer from congestion on a link of the selected path, the developed protocol may not be affected by congestion on a link (if disjoint paths are utilized or if the bottleneck link is not shared by all paths). Furthermore, the protocol implements at the receiver congestion detection and avoidance mechanisms introduced in CUBIC TCP [10], to achieve fairness and reliability.

2.4 *Testbed configuration*

We operate the OpenSAND emulator in transparent satellite mode, using DVB-S2/RCS [11, 12] and applying ULE encapsulation over MPEG-2 TS for the forward link and AAL5 over ATM for the return link, and have set the satellite link propagation delay to 250 ms. In the experiments involving the transport layer protocol of Section 2.3, the maximum chunk size was fixed to 1400 bytes and, unless otherwise noted, the terms packet and chunk are used interchangeably. Measurement results were obtained either using the Wireshark network protocol analyzer or application logs, and mean values of three executions of each experiment are reported.

3. Integration scenarios and performance evaluation

With future content services in mind, we have carried out a set of integration activities to showcase our architecture's support for key functions, such as transparent integration of satellite and terrestrial infrastructure, exploitation of the multicast/broadcast capabilities of both ICN and satellite networking, and in-network caching, while also highlighting our multi-service infrastructure's support for content-based traffic engineering, multisource/multipath transport, and enhanced mobility.

In this section, we present these activities and experimental results that demonstrate the gains of the proposed integrated satellite-terrestrial ICN architecture. The main focus is on video distribution services, but we also show how the architecture supports other (diverse) types of applications (e.g., file transfer).

3.1 *Video streaming transparently utilizing terrestrial ICN multicasting and satellite broadcasting*

This scenario involves video streaming that is sent using multicast from a single publisher (video server) to subscribers connected through a ST. The scenario demonstrates the inherent multicast capabilities of ICN: A delivery tree to all subscribers of a video is created and maintained based on the network topology. Using LIPSIN, forwarding elements do not maintain any state. The multicast tree is encoded into a Bloom filter carried in each packet and a simple AND operation is sufficient to decide if an incoming packet should be forwarded to a particular outgoing interface. The ICN network transparently updates the multicast tree while subscribers enter and leave the video streaming session, by changing the corresponding bloom filter. Hence, the publisher (video server) is not notified, nor are the forwarding nodes affected, when new subscribers enter or leave. Finally, terrestrial ICN multicasting and satellite broadcasting are transparently and uniformly utilized: When a new subscriber is connected to the terrestrial network, ICN multicasting is utilized, whereas when the subscriber is connected through a new satellite terminal, satellite-based broadcasting is utilized.

Table 1: Performance of a video streaming application.

	Subscriber 1	Subscriber 2
Video size (packets)	23940	
Packets lost	798 (3.3%)	798 (3.3%)
Playout interruptions	31	31
Setup delay (ms)	1587	1580
QoE	Good (4)	Good (4)

We experimented with the transmission of a standard definition video file (Microsoft MPEG4-v3-encoded at 30 frames per second) from a publisher connected to the satellite gateway to two subscribers attached to a satellite terminal. The publisher sends content using a single FId and packets are duplicated at the branching point–the satellite terminal; therefore, data traverse the satellite link only once, improving satellite efficiency. We emulated random satellite link unavailability which sums up to 3.5% of the whole experiment duration (we call the related parameter p_u) and measured the packet loss ratio[1], playout interruptions and set up delay, as well as the Quality-of-Experience in terms of the Mean Opinion Score (MOS) from 6 expert viewers[2] who were asked to view and rate the video. QoE values are expressed in terms of the Absolute Category Rating (ACR) scale [15], where each subject rates a video on the 1-5 scale, with a score of 5 representing excellent video quality. The results of our experiments are shown in Table 1.

Both subscribers receive the same number of packets, since packets are dropped on the satellite link, which is shared by the two subscribers. The short playout interruptions within 5 minutes of streaming and the approximately 1.5-second setup delay did not cause significant QoE degradation for the subjects.

3.2 Native content-based traffic engineering

The second scenario demonstrates an ICN network's ability to select and exploit multiple communication paths based on the type of content, but also on user preferences (e.g., considering communication costs) and operator policies (e.g., load balancing across satellite and terrestrial links). This is possible because naming of objects in ICN makes the type of content information available to the TM, which can implement various routing policies without requiring mechanisms such as Deep Packet Inspection (DPI) that would be necessary in legacy IP networks for implementing content-based traffic engineering.

To demonstrate this feature, we have extended the functionality of the domain's Topology Manager (TM) with mechanisms that enforce content/name-based traffic engineering and thus facilitate the application of DiffServ policies. In particular, in our setup the TM is aware of two basic services, `TIME_CRITICAL` and `NON_TIME_CRITICAL`, which in this scenario are associated with the file extensions `.tc` and `.ntc`, respec-

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[1] The number of packets lost was reported by the VLC media player, which was used for media playout. Note that in this experiment we do not use the transport protocol described in Section 2.3. Rather, the video publisher directly uses the Blackadder API to transmit video frames.

[2] Recommendation ITU-R BT.500-13 [13] sets the minimum number of non-expert viewers for a formal video QoE evaluation to 15. Otherwise, the study is considered informal. In our case, test subjects were experts, in the sense that they have expertise in the image artefacts that may be introduced in our system. In a slightly different context (Large Display Digital Imagery), ITU-R BT.1663 [14] suggests that a number as low as five expert viewers is adequate for picture quality evaluation.

Table 2: Content-based path selection performance.

File	`a.ntc`	`b.tc`
Download time (s)	3.46	6.1
Throughput (kb/s)	4824.8	6394.4
RTT (ms)	1172	15
Chunk retransmissions	77	4
Packets lost	69	0

tively. Hence, if a rendezvous is associated with an information item with the `.ntc` extension, the TM will use only paths that contain a satellite link, since the transmission is not time critical. On the other hand, a file with the `.tc` extension will be served by paths that do not contain a satellite link. For the other types of data any combination of routes is possible. Of course, other combinations of rules may be applied (e.g., to use both satellite and terrestrial paths for time critical content).

In this experiment, a publisher attached to the satellite gateway publishes files `a.ntc` (2 MB, 1427 chunks) and `b.tc` (50 MB, 35715 chunks). Publications are stored in the domain's rendezvous point, which in our setup is collocated with the publisher, and are afterwards matched with the corresponding subscriptions from a single subscriber attached to the satellite terminal. As shown in Figure 1, there are two available paths from the publisher to the subscriber. A terrestrial path, which we emulate using an IEEE 802.11g Wi-Fi link with its rate set to 24 Mbps, and a two hop path that contains a satellite and a fixed Ethernet link. File `a.ntc` is transferred exclusively via the latter path, while file `b.tc` is transferred over the former. The two downloads begin almost simultaneously and continue until all data are transmitted. The transport protocol described in Section 2.3 is used and the duration of the satellite link unavailability is 3% of the overall experiment execution time.

Table 2 summarises the results of our experiment. We do not observe a significant difference in the performance of the two flows. As mentioned above, despite the different Round-Trip Times (RTTs) on the two routes, both transmissions achieve a good download rate, due to the implementation of a CUBIC-TCP-like mechanism on the subscriber. The fact that the throughput achieved on the satellite is almost 75% of the respective value on the terrestrial path is a result of the errors on the satellite link and the brief download time which did not permit full utilization of the medium. Note that, in all experiments, we measure network-layer and not application-layer throughput, thus duplicate chunks (due to retransmissions) also contribute to the calculated throughput values.

3.3 Bandwidth aggregation and resilience via multi-path delivery

The third scenario demonstrates ICNs ability to exploit multiple communication paths to fetch pieces of the requested content. Multipath delivery provides two significant advantages: Firstly, increased performance through the aggregation of bandwidth from multiple paths, and secondly resilience to link/node failures or disconnections from one access network technology in the case of multihomed end devices.

Again, a publisher is attached to a satellite gateway and a subscriber is connected to a satellite terminal's LAN, and there are two paths available (satellite and terrestrial; see Section 3.2). Our multipath transport scheme is applied for the delivery of a 50 MB file (35517 chunks). The results of this experiment are shown in Table 3.

Table 3: Multi-path delivery performance.

Download time (s)	35.75
Chunks requested via satellite path	15490
Chunks requested via terrestrial path	20225
Throughput of satellite path (kb/s)	5144
Throughput of terrestrial path (kb/s)	6784
Overall throughput (kb/s)	11928
Chunk retransmissions on satellite path	1107
Chunk retransmissions on terrestrial path	8
Packets lost on satellite path	902
Packets lost on terrestrial path	1

Table 4: Single-path delivery performance.

Download time (s)	65.4
Chunks requested	35715
Throughput (kb/s)	6399.6
Chunk retransmissions	0
Packets lost	0

Our results show that an aggregate throughput of 11928 kb/s is achieved: 6784 kb/s in the terrestrial path and 5144 kb/s in the satellite one. We have configured the probability that the satellite link is unavailable to $p_u = 3\%$. In our receiver-driven transport protocol, the independent transmission of each file chunk requires the successful transfer of two messages (chunk request and chunk reply), and since both chunk requests and responses are routed through the satellite gateway and are thus subject to packet drops, the expected ratio of unsuccessful chunk transfers requiring retransmission is $1 - (1 - p_u)^2 = 5.91\%$, which justifies the measured packet loss rate.

To emphasize the advantages of multipath transmission, a second experiment was conducted, during which the publisher and the subscriber were disconnected from the satellite gateway and terminal respectively, thus being forced to communicate via the single-hop terrestrial link. Table 4 summarizes the results of this experiment.

These results indicate that the subscriber takes full advantage of the terrestrial path, as the entire mediums capacity is used by the CUBIC TCP-like flow. However, the download time increases by 29.65 s. Hence, by not utilizing the additional path, the receiver's performance is reduced. On the other hand, multipath can exploit the bandwidth that is available on all paths between the publisher and the subscriber, improving performance, but also reliability and resilience.

3.4 Performance of in-network caching

One of the features of our ICN architecture is its support for in-network caching. By implementing a chunk-level cache with an LRU (Least Recently Used) replacement rule at the satellite terminal, we can achieve improved performance, but also reduced traffic at the satellite link. In this use case, a home user subscribes to content and receives it via a path composed of two ICN hops (publisher → satellite terminal → user terminal). Chunks of data cached at the satellite terminal are sent to the subscriber (the same subscriber who re-subscribes to the same content item or another user) from the terminal's cache, thus avoiding transmission of the same data over the satellite link.

It is important to note that although caching can be performed using other mecha-

Table 5: File transfer performance with caching disabled.

File	`a`	`b`	`a` (2^{nd} request)
Download time (s)	10.6	11	10.5
Throughput (kb/s)	3809.68	3930	3846
Retransmissions	0	0	0

nisms, such as proxies or CDNs, these are overlay solutions, whereas ICN architectures support caching at the network layer. Additionally, since in ICN content is identified by location-independent names, content with the same name is cached once. This is not the case in legacy IP networks where the same content located in different servers has different URLs, thus treated as different objects and cached independently.

Our experiment involves the publication of files `a` (4.8 MB, 3446 chunks) and `b` (5.2 MB, 3689 chunks). Subscribers request files in the following order: `a - b - a`. Data are delivered either by the publisher or the network storage (caching module) at the satellite terminal. We use the transport protocol described in Section 2.3. Subscribers request each file chunk (Chunk Request) independently and receive the corresponding data (Chunk Reply) from the same path. The caching module monitors chunk request/response headers and locally stores all Chunk Reply packets it forwards. When it receives a request for content that is contained in its cache, the module directly sends the content to the subscriber, without forwarding the initial request. We fix the size of the cache to 7135 chunks (roughly 10 MB with 1400-byte chunks, just enough to store both files) and do not emulate satellite link unavailability. For comparison, we first provide results with the caching module disabled (Table 5).

This comparison reveals a number of interesting tradeoffs. Clearly, the results shown in Table 6 validate that caching offers significant savings in the usage of the satellite link: As expected, the second download of file a is fully served by the cache (100% hit ratio) and the satellite link's utilization drops to 0% (100% traffic reduction compared to not having caching). The time to download the cached file (3^{rd} download) also drops by 71.8% (from 10.5 s to 2.96 s) since in this case only the terrestrial link connecting the cache and the subscriber is utilized. On the other hand, there is a small increase in the time for the first download of file `a` and file `b`, compared to the case where caching was disabled (comparison of download times in Table 5 and Table 6). This is due to retransmissions which take place when caching is enabled[3]. We expect that implementing an exponential back-off mechanism in the congestion control algorithm would improve this behavior.

Further overhead is imposed by the need to look up every requested chunk in the cache, which is more pronounced when cache hit ratios are low, as is the case for the first time a file is downloaded. Appropriate dimensioning of the chunk size, as well as optimization of the cache search module, are thus required to limit these effects.

3.5 Seamless mobility

Finally, we showcase ICN mobility support. In this scenario, a mobile user subscribes to video content and receives it via his satellite terminal. Then, he disconnects from his satellite terminals LAN and attaches to a Wi-Fi hotspot. We demonstrate that he

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[3] Caching influences the estimation of the timeout metric of the congestion control mechanism, leading to packet timeouts, thus retransmissions. The small number of cache hits in the first two file transfers is due to packets inside the cache which are considered lost and thus re-requested.

Table 6: File transfer performance with caching enabled at the satellite terminal.

File	`a`	`b`	`a` (2^{nd} req.)
Download time (s)	12.84	15.34	2.96
Throughput (kb/s)	3160.56*	2828.32	13653.36
Satellite forward link bandwidth usage (kb/s)	3156.32	2825.76	0
Satellite return link bandwidth usage (kb/s)	228.8	205.28	0
Traffic reduction on satellite forward link (%)	-0.49%	-0.36%	100%
Cache hit ratio (packetsFound/packetsRequested)	0.057%	0.066%	100%
Cache state (#packets at the end of file transfer/cache size)	3446/7135	7135/7135	7135/7135
Retransmissions (packets)	166.66	131	2.66
Duplicate packets	17	13.33	2.66

* The measured overall throughput is slightly higher than the bandwidth used on the forward satellite link because chunks which are considered timed out by the transport protocol, but have actually been received by the Blackadder module at the subscriber side, contribute to the calculated value. (These chunks are re-requested and eventually delivered from the cache.)

Table 7: Video streaming performance and data/signalling overhead for a mobile subscriber.

Data loss due to mobility	0
Video QoE (ACR scale)	Good (4)
Service re-establishment delay (ms)	5.74
Signaling overhead (packets)	2
Data overhead (packets)	322

receives the video stream with minimal interruptions and service quality degradation, due to the multicast/broadcast capabilities of ICN: The user is pre-subscribed to the video stream from his upcoming point of attachment (Wi-Fi network). A new path (terrestrial) is added in the delivery structure by the TM and data are simultaneously forwarded to multiple subscriber locations. Service disruption and re-establishment delay are thus minimized as the user hands off.

As Table 7 shows, there is no data loss during the connection re-establishment phase due to the presubscription process and the multicast data delivery. However, during the transition phase, which has a 5.74 ms duration, the subscriber receives duplicate UDP packets until he signals the RP with an unsubscribe message (including the identifier of his original point of attachment). Finally, the signalling overhead is 2 packets, which is the number of the requests that the subscriber sends (one to resubscribe to the item from the new location and another one to unsubscribe from his last location).

4. Conclusion

In this work, we have shown how specific features of ICN and satellite communication technologies can be jointly exploited in a converged Future Internet environment. We presented application scenarios which highlight the potential gains in terms of flexible multipoint delivery, resource savings and improved performance due to caching, content-based traffic management, and enhanced mobility support. Our ongoing work focuses on security requirements imposed by ICN architectures [16] and how the necessary protection mechanisms impact the design of our integrated architecture.

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