DAPHNE: A Disruption-Tolerant Application Proxy for e-Health Network Environments

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Abstract. Future health informatics for personalized e-Health services rely on innovative technologies and systems for transparent and continuous collection of evidence-based medical information at any time, from anywhere, and despite the coverage and availability of communication means. We explore Disruption and Delay Tolerant Networking (DTN) as a novel approach for next-generation e-Health information exchange where end-to-end homogeneous networking connectivity is not available. This setting can occur in both rural and urban environments and in both disaster events and normal day-to-day life. The ability of DTN to provide in-transit persistent information storage allows the uninterruptible provision of crucial e-Health services overcoming network instabilities, incompatibilities, or even absence for a long duration. We further describe the integration efforts for a DTN proxy on an e-Health application and discuss experiences and lessons learned.

Keywords: Health Informatics, Delay Tolerant Networks, Biomedical Informatics, Telemedicine, Health Monitoring.

1 Introduction

E-health stands for the application of Information and Communication Technologies (ICT) to improve the access efficiency, effectiveness, and quality of clinical and business processes utilized by healthcare organizations, medical personnel, practitioners, patients, and consumers in an effort to improve the health status of patients [1]. Personalized e-Health, based on best practices and evidence-based medicine, provisions the delivery of key information services and the facilitation and integration of healthcare allowing local and remote access to health information [2].

The healthcare environment is evolving, with increased emphasis on prevention and early detection of disease, primary care, home care, and intermittent healthcare services provided by medical centers of excellence. Part of the care responsibility is shifting to the hands of the citizen, focusing on wellness and health maintenance, forming a social health network among different actors (patients, healthcare professionals, and careers). The traditional care of *single* doctor-patient relationship is gradually transforming

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towards *shared* or *integrated care*, where a team of healthcare professionals spanning across organizational boundaries is responsible for an individual's healthcare. These trends are accompanied by a significant growth in the development and deployment of e-Health services with increased sophistication, facilitated by intelligent sensors, monitoring devices, handheld or wearable technologies, and the Internet. In this dynamic and diverse environment, information exchange holds a leading role and has a significant impact on the practice of e-Health.

In this paper, we explore disruption-/delay-tolerant networking (DTN), an innovative and promising network technology, as an approach for e-Health information exchange in multiple settings, including those where end-to-end connectivity cannot be realized. We present a prototype Disruption-Tolerant Network Application Proxy for e-Health Network Environments (DAPHNE) and its integration with modern e-Health applications. We discuss trends, challenges and advantages of e-Health on how future e-Health services can be built using DTN technologies.

2 Networking for e-Health Applications

An important challenge for e-Health is to shift the entire system of healthcare, including medical education, evident based predictive medicine, and patient empowerment to a proactive model of care. A clear benefit can be obtained through the use of sophisticated telecommunication services, ubiquitous computing, social user interfaces and wireless communication technologies to create intelligent health spaces accelerating the deployment of future e-Health services [3, 4]. Existing e-Health applications allow monitoring by using several proprietary hardware, software, networking technologies, and medical protocols [5].

The research efforts focus on providing solutions for e-Health services and applications that can: i) provide interoperability among medical information systems through different networking technologies, ii) preserve confidentiality with a high level of security, iii) facilitate mobility and extend monitoring spaces beyond areas with ample connectivity, towards making e-Health services available for anyone, anywhere, anytime, and anyhow, and iv) manage the vast amount of information healthcare services generate and transfer from one repository to another.

There is an apparent need for a new networking paradigm able to integrate multiple sensor streams of medical and environmental devices, responsible for collecting local and global state indicator variables that need to be queried and monitored on regular basis from a dense heterogeneous e-Health enabled network [6]. This new communication environment, a common networking architecture, must be easy to deploy; free of network related disruptions; scalable to hundreds or thousands of devices; allow progressive deployment over time; provide processing, filtering, and aggregation of data; and support remote data collection, accessibility, security, and privacy. The capability to collect clinical information from dispersed points is becoming an urgent need and requirement especially in environments with lack of end-to-end connectivity for both rural and urban settings. The DTN paradigm discussed in the next sections can act as a unifying middleware embedded in the network stack to address the aforementioned issues.

3 Disruption- and Delay-Tolerant Networking

Disruption/Delay-Tolerant Networking (DTN, term used depending on environment context) is a new communication paradigm that addresses issues arising in challenged environments, such as the ones with extremely large delays, intermittent connectivity, and severe disruptions [7]. Originally designed for deep-space communications, it was soon realized that it can support application scenarios in terrestrial environments with heterogeneous networks and harsh connectivity [8]. The two main design characteristics of DTN are a) its ability to span across networks with different network protocol stacks (for example, a TCP/IP and IEEE 802.15.4 network) and b) its ability to support communication between nodes that have no end-to-end connectivity at any given time point. The latter is achieved thanks to DTN's concept of *in-transit persistent storage*, transforming the classical "store-and-forward" networking approach into a "store-*carry*-forward" one [7].

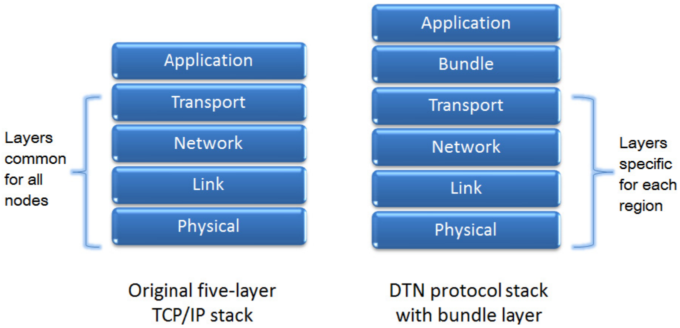

Fig. 1. DTN layering over the Internet model

The IETF RFC 4838 and RFC 5050 define the DTN architecture and the Bundle Protocol (BP) that is used for exchange of information (bundles) among DTN nodes [8, 9]. Figure 1 depicts the placement of the bundle layer over the classical Internet model. In general, the bundle layer exists on top of the transport layer and beyond the application layer. The adaptation of the BP to the specific network stack implemented in a DTN node is realized via a convergence layer (CL) placed among them. This architecture allows bundles encapsulated in BP to transparently travel across regions with different network protocol stacks. Convergence layers have been implemented for a wide range of network protocols, such as HTTP, TCP, UDP, TCP-TLS, NORM, LTP, Ethernet, Bluetooth, AX.25, RS232, and IEEE 802.15.4 LR-WPAN [10].

Applications have been developed for a wide range of devices, including computers, embedded systems, TinyOS-based sensors, and smartphones running Google Android and Apple iOS [10, 11]. Most terrestrial applications target low-resource settings with infrequent communication opportunities, such as Internet connection of remote villages in Africa, wildlife monitoring, communication in mines, and military operations. Experiments were also held on exploring opportunistic or scheduled connectivity using social interactions, vehicular networks, and public transportations. The DTN technology was also demonstrated in e-Health applications, such as a teleconsultation service utilizing diaspora professionals in Ghana [12-14] and a sentinel surveillance application in Tanzania [15].

4 Design of DTN-enabled e-Health Applications

The traditional approach for developing e-Health applications assumes the existence of continuous communication albeit with low bandwidth. If an end-to-end connection is not available, then it is the responsibility of the application to retain the information until such a connection is available. Also, if multiple Internet connections are available (e.g., a WiFi and a 3G one), the application has little control on which one to utilize for a more efficient transmission of the information. Finally, it may be required to implement all the network intelligence within the e-Health application using different platforms and/or for multiple applications. In this case, it is clear that a cross-platform middleware layer can be rather useful.

The DTN architecture can provide a unifying view of e-Health endpoints (proxies), irrespective of the underlying communication technologies and networks they must transverse in order to establish communication. A *common network application programming interface* (API) can provide the necessary middleware adaptation layer as to liberate the e-Health application development from interfacing with different networking technologies. The Bundle Protocol is capable of interfacing with both rich network protocols, as is the case of Internet-based communications, but also with light, non-IP protocols, such as ZigBee and Bluetooth. Furthermore, the bundle protocol specification is open and, if deemed necessary, convergence layers for other protocols can be developed by interested parties. This ability to interface transparently multiple network protocol stacks can be beneficial also in disaster relief operations, where infrastructure cannot be guaranteed and multiple communication technologies may need to co-exist and collaborate [16].

The DTN paradigm works equally well when connectivity exists and when it does not, thanks to its ability of *in-transit persistent storage*. In both cases, the programmer interfaces with one API, independently of underlying networking technology and existence or lack of end-to-end connectivity. The DTN approach *liberates e-Health applications from handling any disconnections* that span delays beyond what current networking technologies can tolerate. This can be beneficial for urban settings, as for example in case of emergencies or when navigating in areas lacking connectivity or when large crowds collect in same space struggling for network access. The availability of an already-deployed application in the field with the inherent capability to communicate in such an environment can be a matter of life and death. Indeed, it may not be possible to deploy after the cause event an e-Health application compatible with the then-available network stacks exactly due to the lack of network infrastructure to support such an operation.

The DTN *late binding approach* allows to *route traffic between e-Health endpoints* that span across different regions, where in each region different network technologies are used and different naming/addressing/binding/routing is used. The DTN approach allows *implanting network intelligence in transferring health related information and* *medical data*. The bundle layer can have knowledge of link quality and quantitate characteristics. It can also have knowledge about the criticality of the information to be transmitted, realizing smart routing. Such routing considers both current network state *and future connectivity opportunities* in deciding which network connection (existing or future) is more appropriate for transmitting the information efficiently and on time.

Not all e-Health information is time-critical; some may be transmitted later on or stored on a device and retrieved on demand at a later time. Even when network coverage exists, it may not be optimal to transmit collected information at a given time moment due to cost, available bandwidth, or required energy. A *smart bundle routing algorithm* can consider all the aforementioned parameters and choose the optimal transmission schedule and/or switch communication networks based on bundle expiration. This complexity is totally hidden from the e-Health application, which needs only to designate the criticality of information to transfer and an expiration date (i.e., “deliver until this date”) and can then pass the responsibility to the DTN layer. The advantage of this approach is that the application is liberated from the complexities of network connectivity management.

The unique ability of DTN to explore not only current but also *future* connectivity opportunities can be very useful in urban settings with multiple connectivity options, as the following example demonstrates. A rich set of sensory media may be collected while commuting from home to work. Given that network connectivity does exist, a traditional e-Health application will try to transmit the information as soon as possible. Using a DTN approach, the application can pass this information to the bundle layer for transmission, designating an expiration date. The bundle layer exploits this information and the fact that a high-speed connection will be available through the office network in a few minutes, based on past connectivity events. Thus, it *defers the transmission of the media-rich sensory data* until then. Suppose now that due to a sad event, the future connection is not realized on time. In this case, the bundle layer activates the alternative, lower-quality links in order to transfer the necessary information before its expiration. It is important to emphasize that in this urban-setting scenario, the *e-Health application is unaware of the entire intelligence planted in the network layers*; the application just delivers the data to be transmitted and never deals with the end-to-end network connection availability.

Last but not least, *security* is addressed in DTN by the already agreed Bundle *Security Protocol* (BSP), described in RFC 6257 [17]. Thus, secure communication between two e-Health DTN endpoints can be implemented across different networks and independently of available networks. From an application designer’s point of view, secure links at the bundle layer can be available no matter what the underlying network offers or lacks. Intelligence may be implanted in the networking stack as to avoid double security, or as to implement secure edges in specific points of the network that may be considered more vulnerable.

5 DAPHNE: An Implementation of a DTN Application Proxy

We implemented DAPHNE, an e-Health application proxy as a proof-of-concept for the applicability and advantages of the DTN technology in such an environment. In our scenario, there is an e-Health application that utilizes medical devices to collect patient's data and transmit them to a remote location for further processing.

We realized DAPHNE on a FitPC Slim computer with a 500 MHz CPU, 512 MB RAM, and 60 GB storage running the Linux operating system and the DTN2 reference implementation of the Bundle Protocol. The computer has an Ethernet, a WiFi, and a Bluetooth interface for connectivity with medical devices. It is connected to the Internet and may face disconnections for multiple reasons. An e-Health application runs as a server component on this computer and acquires data from nearby medical devices using the Continua[1] standard. The collected information is then transmitted for display to a remote host. We used two medical devices in our tests: a commercial SpO_2 device (Onyx® II Model 9560) and a 12-lead ECG (Welch Allyn PRO ECG) connected through a USB interface with the patient unit. The application supports connections from multiple remote ends and broadcasts the information to all connected remote hosts. It also allows the user to configure the frequency of transmission measurements independently of the collection rate and the device-specific biomedical parameters related to sensing. The remote host connects with the server application and is able to display any medical data received on a monitor canvas (i.e., running on a light tablet device). If a disconnection, a delay, or a broken link occurs, then the application is responsible for re-establishing the connection when the problem is resolved.

We bridged the two e-Health application ends with the "*dtntunnel*" proxy available in the DTN2 implementation. This proxy allows the creation of a DTN tunnel over a network that can sustain any delay or disruption, thanks to the in-network storage of the DTN architecture. In the near-end host, the tunnel application receives data from the medical devices and transforms them to bundles. These bundles are stored in the computer until a connection is available with the remote end of the tunnel. In the display application host, the tunnel application receives the bundles from the network and provides a continuous stream of information to the application. In this setup, the two ends of the e-Health applications have an always-on, uninterrupted connection (albeit without data) with the local end of the DTN tunnel. In this way, the two applications need not handle any network connectivity issues at all since their connection is local to the host. We established a testbed between two locations. The medical devices, the sensor application, and the near end of the DTN tunnel were installed at the premises of the Computational Medicine Lab of FORTH-ICS in Crete. The far end of the DTN tunnel and the display application were installed in the premises of the Industrial Systems Institute in Patras. Both systems access the Internet through noisy and unstable wireless connections.

The first set of experiments involved no DTN tunnels. The applications initially established connection and exchanged information (SpO_2 and ECG measurements). After a few seconds, the connection was dropped due to network instabilities and they ceased operation until restarted

The second set of experiments involved the DTN tunnels. In this case, the two applications retained connectivity for prolonged time. Figure 2 depicts a screenshot of the successful experiment. The instable connectivity was apparent, as there were

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[1] `http://www.continuaalliance.org/`

periods of silence (no connection between the two ends of the tunnel). However, once network connectivity was recovered, the tunnel was reestablished automatically and the pending bundles were forwarded transparently to the e-Health application. The DTN network handled all medical-data-related transmissions rendering this simple e-Health application for this urban-setting scenario, unaware of the entire intelligence planted in the network layers; the application just delivered the data to be transmitted and never dealt with the network availability.

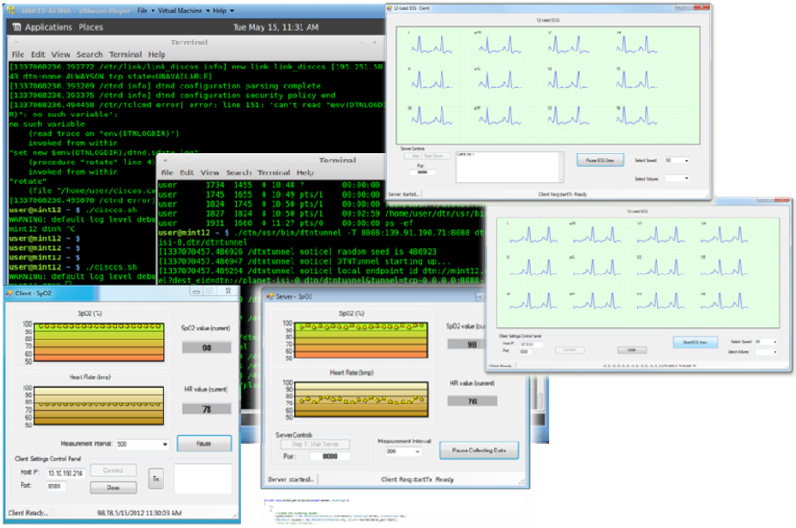

Fig. 2. DAPHNE – DTN Application Proxy for e-Health Network Environments

6 Conclusions and Future Work

The emerging area of e-Health is influenced by factors such as biomedical and clinical incentives, advances in mobile telecommunications and information technology developments, and the socio-economic environment. It aims to the delivery of complex healthcare services enabling personalization, patient inclusion and empowerment with the expectation that such systems will enhance traditional care provision in a variety of situations where remote consultation and monitoring can be implemented despite the lack of end-to-end connectivity.

In this paper, we explored the applicability of delay-tolerant networking as a viable approach to transport information for next-generation e-Health services. We seconded this by presenting an example of a personalized health service provision using medical sensors and e-Health DTN enabled proxies. The diversity of already deployed or envisioned e-Health applications and the heterogeneity of network environments, where the guaranteed end-to-end connectivity assumption cannot be valid, creates an ideal setting for utilizing this promising technology as to allow future e-Health services to overcome the limitations and capabilities of available communication technologies. We aim to further explore this approach and experiment on technology integration in future e-Health services.

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