Service Architecture for Integrating MANETs with Heterogeneous IP Networks

Joe C. Chan, Doan B. Hoang
Advanced Research in Networking Laboratory
University of Technology, Sydney (UTS)
Broadway NSW 2007 Australia

***Abstract* – Multi-hop Ad-hoc Network is promising to extend the reach of current Mobile Internet, and support ubiquitous computing. However, it is hindered by the lack of a flexible network structure bridging the gaps between MANETs and heterogeneous IP networks. This paper introduces a novel Mobile Peer-to-Peer Overlay as an enabling structure for uniting connectivity, mobility and services. Our proposed service architecture allows mobile users to build networks on-the-fly, and capitalize relevant resources in their vicinity for universal communications. Practical implementation of system prototype demonstrates that our proposed framework lays a solid foundation for developing an Integrated Mobile Internet and Ubiquitous Computing.**

I. INTRODUCTION

Wireless Internet is emerging as networks of choice for nomadic users because of the flexibility and freedom it offers. However, contemporary Mobile Internet has its applications limited only within designated coverage areas, and is incapable of dealing with unmanaged network environments. These practical issues drive the global research and developments [1, 2] towards ubiquitous connectivity so that a new era of communications will bring together a multitude of wired and wireless technologies in an ad-hoc manner [3]. The result is a new type of network – Mobile Ad-hoc Network (MANET), which is promising to enhance traditional wireless networks via dynamic multi-hop communications. It also opens the door to ubiquitous computing [4] (also called pervasive computing).

MANET is a distributed mobile system originally designed for military and emergency rescue operations where *a priori* set-up is simply impossible. Its dynamic and transient properties share some similarities and differences [5] with another emerging network model, Peer-to-Peer (P2P) computing. Prior research [6] mainly compared their routing performance by simulations. So far none has maximized the synergies of these two enabling technologies and has a practical implementation. While much of the previous efforts in MANETs focus on routing, the role of MANETs in future network convergence [7] has received little attentions. This paper aims to explore and examine the fundamental aspects of introducing MANETs in heterogeneous wireless/wireline IP networks, from design and architectural perspectives.

The integration of MANETs with various wireless metropolitan-, local-, and personal-area networks (WMAN, WLAN and WPAN) on the Internet leads to a complex network structure, and generate yet many research challenges. Specifically, we focus on a framework proposal to resolve two main issues: (i) *universal connectivity*; and (ii) *MANET location management* in heterogeneous networks. Prior works [8] attempt to solve the former issue by following the traditional Internet model. These approaches force the formless MANETs to operate in structured environment, and inevitably limit the extent of flexibility and freedom that an evolving Mobile Internet can offer. Current mobile positioning and network mobility solutions are mainly infrastructure-driven, hampering the latter issue unresolved for infrastructure-free MANETs. Without a flexible and user-centric network structure, existing solutions are generally insufficient to handle the dynamic and on-demand requirements of MANETs.

In this paper, we propose a novel architecture for Mobile Ad-hoc Systems and Services (AMASS). We name it *AMASS* to reflect our goal of "to come together, and having an effect on forming a large amount," from Merriam-Webster Online Dictionary. The AMASS architecture exploits MANETs and peer-to-peer communication model to create spatial and temporal associations with resources resided in previously disjointed fixed and wireless networks. One essential feature in our architecture is the introduction of a new abstraction layer called *Mobile P2P overlay* to counter deficiencies inherited in our fixed Internet today, namely – transparency, dynamic routing, unique addressing, association, and application independence. It works with our user mobility schemes to address the connectivity and location management issues in heterogeneous IP networks. The result is a flexible network structure for building an "Integrated Mobile Internet" that hides the complexities of underlying networks while providing a universal framework for application services.

Our generalized network structure presents an opportunity to advance fixed and wireless network convergence. Mobile *users* can associate local resources from neighboring *devices*, build wireless on-demand systems and *services* while staying in touch with global community for universal communications, i.e. independent of location, hardware devices, networking technology and infrastructure availability. Its essence is the creation of environments saturated with computing and communications yet gracefully integrated with human users, and so realizes the vision of ubiquitous computing.

The basic idea behind our proposed framework is analogous to how human beings deal with unexplored environments and build up their knowledge. Naturally the way how people behave in unknown settings are to *interact* and *associate* with people in surroundings. Three core design assumptions arise from these settings are:

- Autonomous operations and spontaneous networking are possible. Prior relationships are preferable but not compulsory. Peers and service providers can create relationships on the fly on mutual needs. The relationships tend to be non-deterministic and transient in nature.
- Dynamic interaction to access resources on-demand and in real-time. Convenient solutions for locating service providers will have strong impacts of mobile ad-hoc users' perception of service quality.
- Service location and network topology are uncorrelated. Mobile ad-hoc users can be located behind firewalls and NATs, or on different network transports. Universal location management scheme sought after that peers can work across network boundaries.

In developing this framework, we have implemented an initial system prototype in practical heterogeneous IP networks. Initial experimental results reveal that our proposed architecture using Mobile P2P overlay lays the foundations of developing next generation networks.

The rest of the paper is structured as follows. We first introduce our abstraction model in Section II followed by detailed discussions of five key design considerations in Section III. Section IV presents our proposed architecture. In Section V, we briefly describe our practical implementation and share some testbed experiences. Finally, we summarize our work and outline our future directions in Section VI.

II. Abstraction Model

Current Internet is built on fixed infrastructure connecting diverse computers and networks around the globe through a common Internet Protocol (IP) layer. In the same spirit, we create a common service layer called *Mobile P2P overlay* to integrate MANETs with heterogeneous IP networks (WMAN/WLAN/WLAN and wireline) for all kinds of mobile Internet services. The interaction and adaptation of MANETs with all types of wireline and wireless networks bring us an opportunity to develop wireless on-demand systems and services for universal communications.

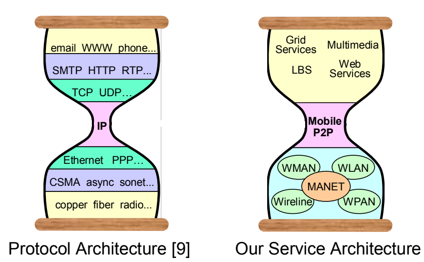

Figure 1 Hourglass Model

The concept of our abstraction layer is best illustrated by analogy with standard IP layer using the "Hourglass model" shown in Figure 1. The Mobile P2P layer connects heterogeneous networks and application services in the same way as IP connects network and application layer protocols. In the *protocol architecture*, IP protocol is used to maximize interoperability and compatibility with existing systems. In our proposed *service architecture*, Mobile P2P overlay is used to unite connectivity, mobility, and services irrespective of its underlying physical networks. The abstraction model is narrow at the Mobile P2P layer for minimizing the number of service interfaces, yet maximizing the number of application services that can be built over the P2P interfaces. It also maximizes the number of usable networks by masking out the differences between network technologies.

The Mobile P2P layer is designed to alleviate five lost features [9] inherited in our Internet today. The main reasons and its corresponding benefits for developing this new abstraction model are summarized as below:

1. **Transparency**: Current TCP/IP assumes wired links and not optimize for wireless (TCP over wireless problems). Our new scheme extracts physical data from underlying networks through open APIs for the layers above.
2. **Dynamic Routing**: Current IP routing designed for static or slowly changing networks. Our new scheme accounts for dynamic wireless topologies enabling intelligent route selection and service adaptation per link basis.
3. **Unique Addressing**: Current IPv4 addressing scheme (and future IPv6) has yet to unique identify users. Our new scheme decouples user naming from hardware addressing by a unique URI addressing.
4. **Association**: Current service discovery mechanisms mainly rely on central directory services such as DNS, SLP for naming and services discovery. Our new scheme builds on a distributed approach to maintain "bonding" between users, devices, and services.
5. **Application Independence**: Current application designs are network-orientated and terminal specific. Our new scheme offers a uniform development environment irrespective of its underlying network types.

For example, application developers can design advanced location-based services (LBS) for mobile ad-hoc users without tracking their individual clients. The ad-hoc users may travel across different networks quite frequently, i.e. occasionally directly connect to office LAN, sometime indirectly connect to Internet through their home WLAN, or even isolate in a MANET island. In any case, the application developers shall only deal with a single Mobile P2P layer that provides both physical and logical location data.

III. Design Considerations

This section discusses five key design considerations that contributed to the resolution of two main issues previously identified: (i) *universal connectivity* requires the support of mobile ad-hoc users with all types of operations – *discrete* cooperative networks, direct or indirect access to local and global resources, as depicted in Figure 2; and (ii) *MANET location management* in heterogeneous networks requires transparent positioning and mobility functions independent of underlying networks and supporting infrastructure, while still be interoperable with global communication infrastructure.

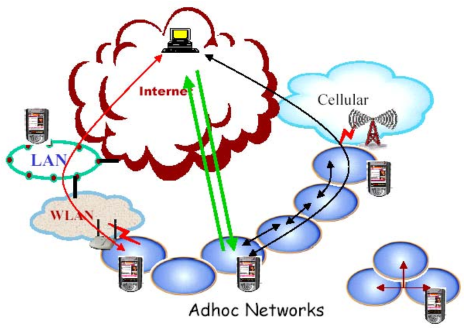

Figure 2 MANETs in heterogeneous networks

A. Mobile Peer-to-Peer Overlay

Current IETF MANET WG in its present form focus only on routing which are designed without considering any specific applications. So a self-organizing structure is sought running on top of MANET core routing protocols to provide basic naming/addressing, peers and services discovery. We propose Peer-to-Peer (P2P) Overlay as a way of structuring distributed applications such that individuals are able to join, participate, and contribute to spontaneous community. The result is a complete Mobile P2P system deployable in an ad-hoc fashion, which alleviates the necessity of centralized management and control. Integrating MANETs with P2P-style applications also yields a more social style of computing [10] for users with the ability to dynamically search and share resources within their intimate community. It also enables mobile ad-hoc users to communicate in heterogeneous networks. This brings us a step forward to network convergence, and complements resources and knowledge in fixed and wireless networks.

B. Internet Interworking

Standard IP routing protocols do not fit well with formless MANETs. Previous works [8] focus on integrating Mobile IP with MANETs for Internet connectivity. These proposals rely on multi-hop default routes or explicit host route entries forwarding traffic to an Internet gateway. Sophisticated IP address reconfiguration [11, 12] are enforced striving for unique topologically correct addresses. Unlike in the fixed networks, IP address in MANETs is merely used as identification and has no routing purpose. MANETs handle routing using a flat address space. We argue that the dynamic and transient properties of MANETs invalidate many structural assumptions made in these approaches, and the current solutions are far from perfect for handling spontaneous MANETs effectively.

Our MANET and Internet interworking scheme exploits the Mobile P2P overlay by abstracting underlying network dependencies, and providing a uniform peer addressing scheme. Internet connection is merely one of the many services offered by ad-hoc community. Device willing to share its Internet connection can nominate itself to be a gateway providing interworking functions. This allows ad-hoc nodes that do not have global routable IP addresses to communicate with the Internet via the gateway's public IP address.

C. Intelligent Overlay Routing

Explicit gateway attachment is another puzzle of using Mobile IP for MANETs attaining its global connectivity. Hop count is typically the only metric assisting multiple gateway selection (or foreign agent handoff) as demonstrated in MIPMANET [13]. The result is a rigid MANET ideal for operating in "long-term parking" environment. However, change of network settings for application specific requirements and service adaptation are unfeasible in these fragmented MANETs. On the contrary, we approach the problem by exploiting logical P2P topology on top of physical MANET topologies. This allows MANET clients to link with multiple gateways simultaneously, resembling the idea of "soft handoff" in CDMA systems. These gateways may be of same or different network transport types so that mobile ad-hoc users could have optimal path selection upon their current needs. For instance, 3G or WLAN has different cost functions. While in MANET attached mode, "Soft states" are always maintained in individual "home" system providing a helicopter view for service adaptation, i.e. matching peer application requirements with instantaneous network environments. The Mobile P2P overlay then allows intelligent route decisions to be made in directing traffic dynamically and efficiently.

D. Infrastructure-free Positioning

Current mobile positioning systems are generally tied into a particular wireless technology built on fixed infrastructure such as GPS, Cellular, WLAN and RFID for locating mobile users outdoors. Therefore continuous services are not guaranteed and limited by its coverage. There also exists a variety of experimental location systems for ubiquitous computing [14] such as ParcTab, Active Badge, Cricket, RADAR and Smart Floor. However, those are specialized indoor systems requiring expansive infrastructure of which spontaneous MANETs can hardly afford. Previous MANET positioning proposals [15] rely on geometric and mathematical transformation, and its complex computation requirements present a hurdle for resource-limited mobile devices. They are generally incapable of supporting mobile clients in heterogeneous networks, i.e. roaming outdoor and indoor across WAN, WLAN and WPAN.

In contrast, our terminal-based approach provides an infrastructure-free positioning solution for MANETs. Its generalized location model allows a truly ad-hoc user positioning experience through dynamic interaction of multiple networks. Its essence is the creation of a communication environment where any MANET nodes knowing its physical location would share its location data with the neighborhoods in an open way [JSR-179]. A new joined node simply estimates its location by information exchange with its neighbors. This dynamic self-learning process would illuminate the entire MANET as for wireless sensor networks in [16], and the iterative operations would improve its accuracy over time. The scheme also make use of Location Stack [17] which converts the raw sensor data extracted from multiple wireless interfaces into location measurements.

E. *Application Layer Mobility*

Mobile IP [RFC 3344] is the present network mobility solution for roaming in heterogeneous IP networks. It is not taking off as anticipated partly due to its stringent requirements of prior service agreement and supporting infrastructure. All these demolish the spontaneous and autonomous assumptions that we have previously made for developing mobile ad-hoc services. In addition, Mobile IP is a terminal-based solution restricting roaming users with their sole device.

In contrast to the hardware specific solution, we adopt a user-centric approach by utilizing peer-to-peer signaling to locate mobile users both inside and outside MANETs. Mobile users within MANETs are able to see each other by peer discovery in the Mobile P2P overlay. Application layer mobility [18, 19] using Session Initiation Protocol (SIP) would take into effect for user tracking whenever MANET users attain global connectivity. The users then publicize themselves for global reach as well as retrieving non real-time service such as email or fax. Three enhanced mobility models offered in this approach are: (i) *Personal Mobility* – using different IP devices while keeping the same address, (ii) *Session Mobility* – keeping the same session while changing IP devices, and (iii) *Service Mobility* – keeping personal services while moving between networks. The concept of user mobility allows mobile ad-hoc users to associate relevant resources in the local community for universal communications, i.e. nearby video conferencing devices, printers and fax machines.

IV. ARCHITECTURE

This section presents our AMASS architecture leading to wireless on-demand systems and services. By exploiting our adapted hourglass model in Section II, resources and knowledge resided in fixed and wireless networks can complement each other. New application services can be developed independently without consideration of underlying networks and infrastructure availability. Mobile P2P overlay is used as an abstraction layer enabling mobile users to create spatial and temporal associations with local resources for universal communications.

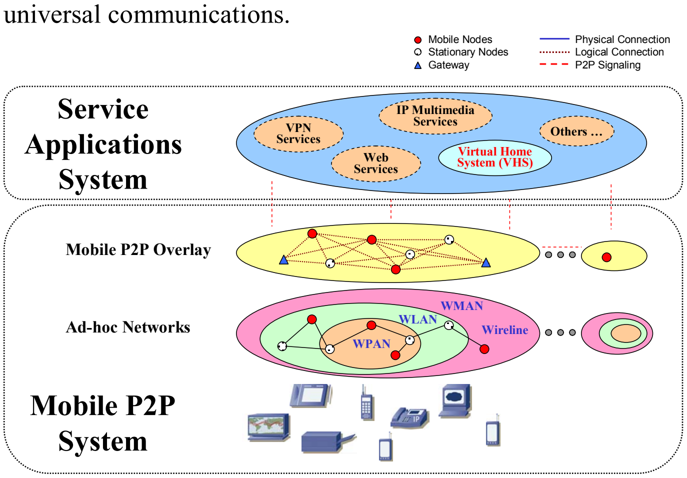

Figure 3 Architecture for Mobile Ad-hoc Systems and Services (AMASS)

Our asynchronous messaging-based architecture is built on a peer-to-peer communication model to integrate discrete MANETs seamlessly into heterogeneous IP networks, as shown in Figure 3. *Mobile Peer-to-Peer System* is a distributed middleware platform ideal for discrete cooperative MANETs where neither centralized coordination nor administration is necessary. It addresses the demand of direct communication needs by creating spontaneous community. Whenever the Mobile P2P system has global connectivity, it works with its peer system and other applications systems by generic P2P signaling. In this paper, we focus on a specific application system – *Virtual Home System (VHS)* utilizing SIP to demonstrate our compatibility with existing systems.

A. *Mobile Peer-to-Peer System*

Each participating node in our Mobile P2P system is an independent network entity capable of multi-hop ad-hoc communications. The Mobile P2P system creates an impromptu community irrespective of its physical link technologies and global connectivity for direct information exchange and instant resources sharing. It consists of two main layers: (i) *Ad-hoc Network layer*, and (ii) *Mobile P2P Overlay*. The Ad-hoc Network layer includes wireless hardware and MANET routing software offering homogeneous connectivity among collaborative devices with same wireless interfaces. These nodes act as a router forwarding traffic toward its destination contained by its physical boundary, i.e. supporting wireless multi-hop communications within its network type.

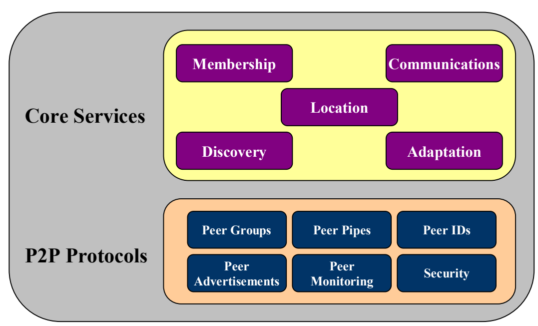

Figure 4 Mobile P2P Overlay

Mobile P2P Overlay is used to abstract underlying network dependences. With advanced short-range wireless technologies such as IEEE 802.15 Ultra-wide Band (UWB) or Bluetooth, the overlay extends the physical boundary of MANETs into logical topology supporting heterogeneous IP networks. As shown in Figure 4. the Mobile P2P Overlay includes the following core services: (i) *Membership Services* offers single sign-on, naming, profile and identity features; (ii) *Discovery Services* for peer/resource discovery and caching; (iii) *Communication Services* for Internet interworking, intelligent routing, session control, presence and service delivery; (iv) *Location Services* for infrastructure-free positioning, and user mobility management functions; (v) *Adaptation Services* for application and network services adaptation.

The virtual overlay network also contains a set of simple and open P2P protocols to allow infrastructureless MANETs operating with a uniform address space. Besides, these P2P protocols provide essential network-level functions for discovering, grouping, and communication among each others. A mediating gateway is used to attain global connectivity and integrate the system as part of the global communication infrastructure. All network entities (i.e. users, devices, and services) are identified by unique names expressed in URI. The system exploits XML to describe device location and user preferences for positioning and mobility management.

Resource discovery is accomplished by individuals broadcasting its service capabilities in a form of XML-based advertisement messages. This allows infrastructureless MANET users to discover other peers and resources without relying on central directory services such as DNS, Jini, and SLP. For instance, a public photo printer may announce its features and charging model on an application layer. Mobile users can then select available services upon his/her own needs to locate and utilize the printing service.

B. *Virtual Home System*

The Virtual Home System (VHS) is a service integration system providing interworking functions for Mobile P2P system with external systems. It aims to enrich mobile users with virtual home experiences for universal communications. As depicted in Figure 5, the VHS serves as a rendezvous server providing proxy, redirection, and registration functions for managing IP mobile multimedia traffic. Its integrated location server also provide a persistent storage of location data enabling application servers to deliver personalized mobile services pertinent to user location as per their preferences and subscriptions.

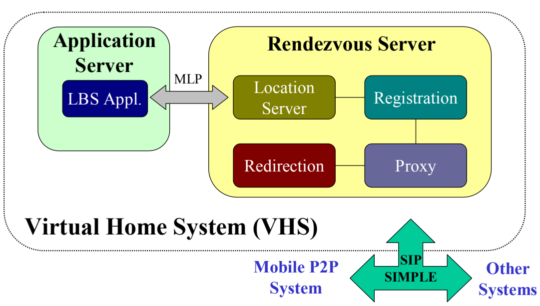

Figure 5 Virtual Home System (VHS)

The VHS utilizes IETF's SIP [RFC 3261] to work with the Mobile P2P system providing intelligent overlay routing in heterogeneous networks. SIP is used as "P2P signaling" offering session control, application-layer mobility support, and location-based push mechanisms. SIP is chosen as the P2P signaling simply because of its flexibility and freedom offer to users and its important roles to be played in future IP-based Multimedia systems. SIP already has a namespace ENUM supports by the DNS (URIs) and not dependent on IP, a way to signals peers through NAT boxes.

C. *Operations*

Members of the Mobile P2P system should first sign-in a "common group" using personal mobile devices with their unique name and password. This primitive process offers a uniform space allowing all members to discover and communicate with each other anywhere in the world. Some stationary nodes may also join this public or private group to offer its resources such as Internet connection, printer, video conferencing terminals…etc, subject to its service model. Whenever these client devices are within range to each other, they would work together as a team leading to a wireless ad-hoc service community where local resources could be shared by individual at its will. The mobile clients can also derive its physical location from our dynamic self-positioning process in an infrastructure-free MANET environment.

Our single sign-on feature ensures the Mobile P2P members to log on their respective VHS automatically whenever global connectivity is available. The members will then be publicized themselves for global access simply by reporting their latest "capability statements" (i.e. associated resources from his/her neighborhoods), and current "location data" to the central location server. Apart from the logical location is sent for intelligent routing and service adaptation purposes, physical location is also essential to offer spatial locality relationships and enable mobile content customization. External users can always contact the member's VHS for intelligent route decisions, and effective peer-to-peer communications can be established accordingly.

V. IMPLEMENTATION

We have developed an initial system prototype for proof-of-concepts and experimental development. The prototype gives us a practical environment to evaluate and demonstrate our proposed framework in actual wired and wireless IP networks. It maximizes the use of off-the-shelf fixed/mobile equipments and standardized interfaces to ensure interoperability with existing networks and systems for pervasive applications.

The proposed Mobile P2P system is built on Sun's JXTA[1] platform on top of MANET devices. The advantages of building the Mobile P2P Overlay utilizing generic JXTA protocols are that the concepts of P2P overlay networks and platform independency can be leveraged. The Ad Hoc Network layer incorporates one of the well-known MANET Reactive Routing Protocols (MRRP) called Ad-hoc On-demand Distance Vector (AODV) running on top of IEEE 802.11 WLAN in ad-hoc mode to support multi-hop wireless communications. AODV-UU from Uppsala University is deployed as a user-space daemon that alters the kernel routing table dynamically as per the ever changing topology, and provides Internet connectivity through gateway support with tunnels [20]. The Virtual Home System (VHS) is provisionally realized by SER (SIP Express Router) platform, an open source implementation of SIP server from IPTEL.

[1] Sun's Project JXTA, http://www.jxta.org

A. *Experimental Testbed and Experiences*

We have deployed an experimental network (Figure 6) in our laboratory for data collection and performance evaluation where *feasibility* and *usability* were the two main focuses.

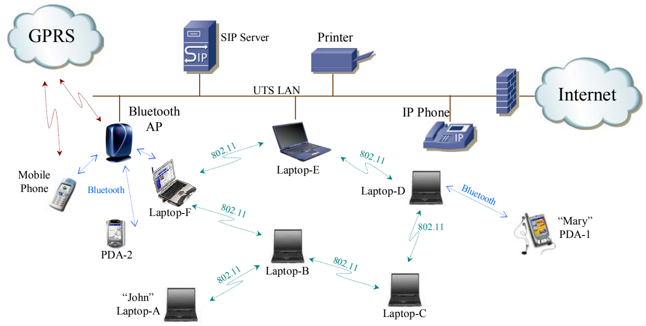

Figure 6 Mobile Ad-hoc Peer-to-Peer Testbed

Several test cases were performed to examine our proposed service architecture in respect of transparency, dynamic routing, unique addressing, association, and application independence. We used simple P2P instant messaging and file sharing applications to illustrate how mobile users are able to discover, locate, and communicate with each other irrespective of their underlying networks and physical hardware. Without any infrastructure, our researchers using diverse terminal types (laptop, PDAs, and mobile phone) were able to self-organize and form a spontaneous community for group and/or private communications. Users/Services simply identified each other using their preferred name. Neither *a priori* route setup, nor knowledge of network topology was necessary. Instant networking were spanned multiple domains using various link layer technologies – Ethernet, IEEE 802.11b, Bluetooth, and GPRS. For instance, "John" sends an instant chat message from his laptop-A to "Mary" who is currently reachable by her PDA-1 through IEEE 802.11 multi-hop routing (laptop-B/C/D) and direct Bluetooth connection.

We showed that the seamless integration of MANETs with heterogeneous IP networks allows mobile users to access local services such as printer and IP phone in real-time and on-demand. We also found that Mobile P2P overlay is an effective abstraction layer uniting connectivity, mobility and services for developing an integrated Mobile Internet.

VI. Conclusions

This paper presents our novel architecture for mobile ad-hoc systems and services (AMASS). The AMASS architecture has several distinct features. First, it maximizes the synergies of MANETs and P2P for building wireless on-demand systems and services. MANETs provide dynamic physical connectivity while P2P offers dynamic associations of entities (users, devices, and services) for direct resources sharing. Second, its Mobile P2P overlay unites mobility, connectivity, and services for universal communications. Our user-centric connectivity and location management schemes allow dynamic service adaptations pertinent to user location, application requirements, and network environments. Third, it presents a flexible network structure stimulating fixed and wireless networks convergence. Our abstraction model allows diverse Mobile Internet application services to be built independent of underlying networks. The result is an "Integrated Mobile Internet" targeting to enhance our future living environments.

Initial implementation of the architecture demonstrates that our proposed framework promises a solid foundation for developing future wireless on-demand services and ubiquitous computing. We are currently in the process of integrating our Mobile P2P system with SIP-based IP multimedia systems. We anticipate that this unique combination will trigger many ad-hoc services to be developed.

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