A Cellular IP Testbed Demonstrator

Andrew T. Campbell, Javier Gomez, Sangyho Kim, Bill Paul, Takuya Sawada, Chieh-Yih Wan
Center for Telecommunications Research, Columbia University, New York
cellularip@comet.columbia.edu

András G. Valkó*, Zoltan Turanyi
Ericsson Research
(andras.valko, zoltan.turanyi)@lt.eth.ericsson.se

Abstract– **Cellular IP is a wireless Internet access technology that operates on mobile hosts, base stations and Internet gateways. Cellular IP combines the capability of cellular networks to provide high performance handoff and efficient location management of active and idle mobile users with the inherent flexibility, robustness and scalability found in IP networks. In this paper we provide an overview of the Cellular IP routing, handoff and paging algorithms and their implementation in a pico-cellular testbed that will be demonstrated at the Sixth IEEE International Workshop on Mobile Multimedia Communications (MOMUC99). The protocol has been under development at Columbia University for the past several years initially as a joint project between the Center for Telecommunications Research and Ericsson Research. The source code for Cellular IP v1.0 is freely available (comet.columbia.edu/cellularip) for experimentation.**

I. INTRODUCTION

Cellular IP inherits principles of cellular systems for mobility management, passive connectivity and handoff control, but is designed based on the IP paradigm. The universal component of a Cellular IP network is the base station which serves as a wireless access point but at the same time routes IP packets and integrates cellular control functionality traditionally found in mobile switching centers (MSC) and base station controllers (BSC). The base stations are built on regular IP forwarding engines, but IP routing is replaced by Cellular IP routing and location management. Cellular IP access networks are connected to the Internet via gateway routers. Mobility between gateways (i.e., Cellular IP access networks) is managed by Mobile IP while mobility within access networks is handled solely by Cellular IP. Mobile hosts attached to the network use the IP address of the gateway as their Mobile IP care-of address. Figure 1 illustrates the path taken by packets addressed to a mobile host. Assuming Mobile IPv4 [1] and no route optimization, packets will be first routed to the host's home agent and then tunneled to the gateway. The gateway "detunnels" packets and forwards them toward base stations. Inside the Cellular IP network, mobile hosts are identified by their home addresses and data packets are routed without tunneling or address conversion. As discussed later, the Cellular IP routing protocol ensures that packets are delivered to the host's actual location. Packets transmitted by mobile hosts are first routed to the gateway and from there on to the Internet.

In Cellular IP, location management and handoff support are integrated with routing. To minimize control messaging, regular data packets transmitted by mobile hosts are used to establish host location information. Uplink packets are routed from a mobile host to the gateway on a hop-by-hop basis. The path taken by these packets is cached by each intermediate base station. To route downlink packets addressed to a mobile host the path used by recent packets transmitted by the host is reversed. When the mobile host has no data to transmit then it periodically sends empty IP packets to the gateway to maintain its downlink routing state. Following the principle of passive connectivity mobile hosts that have not received packets for a certain period of time allow their downlink "soft-state routes" to timeout and be cleared from the routing cache. In order to route packets to idle hosts a Cellular IP mechanism called paging is used.

II. ROUTING

A Cellular IP gateway periodically broadcasts a beacon packet that is flooded in the access network. Base stations record the interface they last received this beacon through and use it to route packets toward the gateway. All packets transmitted by mobile hosts regardless of their destination address are routed to the gateway using these routes.

As these packets pass each node on route to the gateway their route information is recorded as follows. Each base station maintains a routing cache. When a data packet originated by a mobile host enters a base station the local routing cache stores the IP address of the source mobile host and the interface over which the packet entered the node. In the scenario illustrated in Figure 1 data packets

*Visiting Scientist, Center for Telecommunications Research, Columbia University, New York.

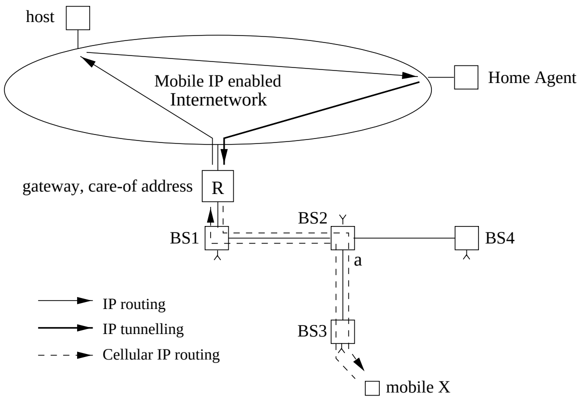

Figure 1: A Cellular IP Access Network

are transmitted by a mobile host with IP address **X** and enter **BS2** through its interface **a**. In the routing cache of **BS2** this is indicated by a mapping **(X,a)**. This mapping remains valid for a system specific time route-timeout and its validity is renewed by each data packet that traverses the same interface coming from the same mobile host. As long as the mobile host is regularly sending data packets, base stations along the path between the mobile host's actual location and the gateway maintain valid entries in their routing cache forming a soft-state route between the mobile host and gateway nodes. Packets addressed to the same mobile host are routed on a hop-by-hop basis using the established routing cache.

A mobile host may sometimes wish to maintain its routing cache mappings even though it is not regularly transmitting data packets. A typical example of this is when the host is the receiver of a stream of UDP packets and has no data to transmit. To keep its routing cache mappings valid in an access network the mobile host transmits route-update packets at regular intervals called route-update time. These packets are empty data packets addressed to the gateway. Route-update packets have the same effect on routing cache as normal data packets; however, they do not leave Cellular IP access networks.

III. HANDOFF

The Cellular IP hard handoff algorithm is based on a simple approach to mobility management that supports fast handoff at the price of potentially some packet loss. Handoff is initiated by mobile hosts in a Cellular IP access network. Hosts listen to beacons transmitted by base stations and initiate handoff based on signal strength measurements. To perform a handoff a mobile host has to tune its radio to the new base station and send a route-update packet. This creates routing cache mappings on route to the gateway hence configuring the downlink route to the new base station. Handoff latency is the time that elapses between the handoff and the arrival of the first packet through the new route. For hard handoff this equals the round-trip time between the mobile host and the cross-over point which is the gateway in the worst case. During this time, downlink packets may be lost. The mappings associated with the old base station are not cleared at handoff, rather, they timeout as the associated soft-state timers expire.

Before the mappings timeout, a period exists when both the old and new downlink routes are valid and packets are delivered through both base stations. This feature is used in the Cellular IP semisoft handoff algorithm that improves handoff performance but still suits the lightweight nature of the base protocol providing probabilistic guarantees instead of fully eliminating packet loss. Semisoft handoff adds one additional state variable to the existing mobile state maintained at mobile hosts and base stations. The semisoft handoff procedure has two components. First, in order to reduce handoff latency, the routing cache mappings associated with the new base station must be created before the actual handoff takes place. When the mobile host initiates a handoff, it sends a semisoft packet to the new base station and immediately returns to listening to the old base station. While the host is still in contact with the old base station, the semisoft packet configures routing cache mappings associated with the new base station. After a semisoft delay, the host can perform a regular handoff. The semisoft delay can be an arbitrary value between the mobile-gateway round-trip time and the route-timeout. The delay ensures that by the time the host tunes its radio to the new base station, its downlink packets are delivered through both the old and new base stations.

While the semisoft packet ensures that the mobile host continues to receive packets immediately after handoff, it does not, however, fully assure smooth handoff. Depending on the network topology and traffic conditions, the time to transmit packets from the cross-over point to the old and new base stations may be different and the packet streams transmitted through the two base stations will typically not be synchronized at the mobile host. If the new base station "lags behind" the old base station, the mobile host may receive duplicate packets. Reception of duplicate packets in this case is not disruptive to application operations. If, however, the new base station "gets ahead" then packets will be deemed to be missing from the data stream observed at the receiving mobile host. The second component of the semisoft handoff procedure is based on the observation that perfect synchronization of the two streams is not necessary. The condition can be eliminated by temporarily introducing into the new path a constant delay sufficient to compensate, with high probability, the time difference between the two streams. This can be best achieved at the cross-over switch that understands that a semisoft handoff is in progress due to the fact that a semisoft packet has arrived from a mobile host that has a mapping to another interface. The mapping created by the semisoft packet has a flag to indicate that downlink packets routed by this mapping must pass a "delay device" before transmission. After handoff, the mobile host will send data or route-update packets along the new path which will clear this flag and cause all packets in the delay device to be forwarded to the mobile host.

IV. PAGING

Cellular IP defines an idle mobile host as one that has not received data packets for a system specific time active-state-timeout. In this respect, idle mobile hosts allow their respective soft-state routing cache mappings to time out. These hosts transmit paging-update packets at regular intervals defined by paging-update-time. The paging-update packet is an empty IP packet addressed to the gateway that is distinguished from a route-update packet by its IP type parameter. Paging-update packets are sent to the base station that offers the best signal quality. Similar to data and route-update packets, paging-update packets are routed on a hop-by-hop basis to the gateway. Base stations may optionally maintain paging cache. A paging cache has the same format and operation as a routing cache except for two differences. First, paging cache mappings have a longer timeout period called paging-timeout. Second, paging cache mappings are updated by any packet sent by mobile hosts including paging-update packets. In contrast, routing cache mappings are updated by data and route-update packets sent by mobile hosts. This results in idle mobile hosts having mappings in paging caches but not in routing caches. In addition, active mobile hosts will have mappings in both types of cache. Packets addressed to a mobile host are normally routed by routing cache mappings. Paging occurs when a packet is addressed to an idle mobile host and the gateway or base stations find no valid routing cache mapping for the destination. If the base station has no paging cache, it will forward the packet to all of its interfaces except the one the packet came through. Paging cache is used to avoid broadcast search procedures found in cellular systems. Base stations that have paging cache will only forward the paging packet if the destination has a valid paging cache mapping and only to the mapped interface(s). Without any paging cache the first packet addressed to an idle mobile host is broadcast in the access network. While the packet does not experience extra delay it does, however, load the access network. Using paging caches, the network operator can restrict the paging load in exchange for memory and processing cost.

Idle mobile hosts that receive a packet move from idle to active state, start their active-state-timer and immediately transmit a route-update packet. This ensures that routing cache mappings are established quickly potentially limiting any further flooding of messages to the mobile host.

For full details of the protocol specification and performance see [2] and [4], respectively.

V. IMPLEMENTATION

Cellular IP is based on modular software design and is implemented on FreeBSD and NT software platforms. The protocol comprises base station and mobile host modules. Both protocol modules rely on a common system module. In the case of the FreeBSD implementation the system module filters IP packets from the physical medium to move them to user space and delivers packets processed in the user space to the required network interface. The system module uses the Berkeley Packet Filter's Packet Capture library (PCAP). PCAP was designed to capture packets for statistical purposes but can also be used to forward packets to a network interface. In what follows, we provide an overview of the base station and mobile host protocol modules.

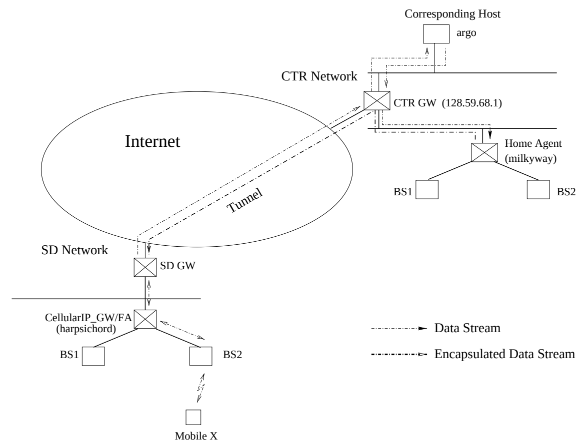

Figure 2: A Cellular IP Testbed Demonstrator

V.1. BASE STATION MODULE

A Cellular IP base station serves as wireless access point, router and location manager. In addition, our implementation allows a base station to implement gateway functionality relying on the kernel's IP routing function. In our implementation, the uplink and downlink interfaces are configured by network management instead of gateway beacon messages. Along with the routing and (optional) paging cache, the most important functions of the base station include: (i) a paging update function, which maintains the paging cache; (ii) a classifier, which parses uplink packets and selects those that update the routing cache (data, route-update and semisoft packets); (iii) a route update function, which maintains the routing cache; (v) a routing cache lookup function, which searches the routing cache for mapping(s) associated with the destination mobile host; (iv) a paging cache lookup function, which searches the paging cache for mappings if a routing cache mapping was not found; (vi) a forwarding engine, which forwards downlink packets to the interface selected by the routing cache lookup in the first instance and by the paging cache lookup if no route was found.

Note that the protocol module is not aware whether a downlink interface is a wireless interface or a wired connection to another base station. Currently our implementation uses IEEE 802.11 2/6Mbps WaveLAN and 11 Mbps Aironet radio devices, but the protocol module can transparently interwork with other radio interfaces that we are writing device drivers for. In addition to the functions described above, the base station contains beacon generators for each wireless interface. In Cellular IP, the content of the beacon is similar to the standard WaveLAN beacon but is extended to include the gateway's IP address.

V.2. MOBILE HOST MODULE

The mobile host module is implemented as a deamon which runs in user space in our FreeBSD experimental testbed. The standard IP protocol stack is not touched by the Cellular IP deamon and applications are unaware of mobility. The main function of the deamon includes: (i) a handoff controller, which keeps statistics of measured beacon strengths and performs handoffs; (ii) a protocol state machine, which has two states: active and idle. In idle state, any incoming packet triggers a transition to active state. At the same time, a timer is initiated that is reset by each incoming packet. The expiration of the timer triggers the transition to idle state; and (iii) a control packet generator, which periodically transmits route-update or paging-update packets as required by the state machine.

VI. THE DEMOSTRATOR

Two aspects of the Cellular IP protocol will be demonstrated at the workshop. First, we will show how Cellular IP and Mobile IP interwork to provide support for macro-mobility between Internet gateways. Second, we will show the performance of Cellular IP in support of micro-mobility in a pico-cellular testbed.

The Cellular IP testbed comprises three multi-homed base stations supporting WaveLAN and Aironet high speed radio access. The testbed for macro- and micro-mobility is illustrated in Figure 2. The base stations form a Cellular IP access network connecting into the Internet via a gateway PC. The mobile hosts comprise multiple notebooks and palmtop devices supporting web and TCP/IP applications (e.g., continuous media applications, portals). At the mobile devices side Cellular IP runs on NT and FreeBSD platforms. We will source media from multiple servers at Columbia and show high performance handoff between Cellular IP base stations for micro-mobility (which is in the order of 4 ms. handoff time).

Evaluation of the protocol operating in this pico-cellular wireless testbed is very promising in terms of the performance of handoff, the network overhead associated with supporting mobility management and the scalability of the protocol to be configured to meet the requirements of widely different environments.

VII. CONCLUSION

This paper has provided an overview of the Cellular IP protocol which we have submitted [2] to the IETF IP Routing for Wireless/Mobile Hosts Working Group for discussion. Cellular IP represents a new approach to IP host mobility that incorporates a number of important cellular system features but remains firmly rooted in IP.

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