

# DISTRIBUTED SOFT HANDOFF IN ALL-IP WIRELESS NETWORKS

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## Abstract

Two key problems need to be solved in order to realize soft handoff in wireless IP (Internet Protocol) networks: 1) Data distribution: multiple streams of the same IP traffic have to be distributed via multiple wireless base stations to the same mobile station, 2) Data content synchronization: pieces of data arriving at the mobile station at the same time from different base stations should be copies of the same data for the mobile station's radio system to correctly combine the pieces into a single copy. Solving these problems in a distributed all-IP wireless network remains a challenge. This paper presents a new solution that consists of two main components: 1) a method that uses *shadow addresses* to realize data distribution with little signaling and 2) an IP-layer procedure performed by *base stations* to ensure data content synchronization at the mobile station.

## 1 Introduction

Handoff is a process that allows a mobile station's session in progress to continue without interruption when a mobile station (MS) moves from one cell (i.e., the coverage area of one wireless base station) to another. Handoff process can be hard or soft. With soft handoff, a mobile station communicates with multiple wireless base stations (BSs) simultaneously. Soft handoff is an effective way for increasing the capacity, reliability, and coverage range of CDMA networks. It can also provide more time for carrying out the handoff procedure.

This paper presents a novel solution for soft handoff in all-IP wireless networks that use IP-based wireless base stations (iBSs). As described in [1], all-IP wireless networks have the following unique characteristics that differentiate them from most existing wireless networks:

- The iBSs use IP protocols for signaling and/or data transport.
  - The iBSs may function autonomously.
  - The iBSs are interconnected via an IP network that could have any arbitrary network topology.
  - Cells may be arranged in any arbitrary configuration.
- Two key requirements for realizing soft handoff are:
- *Data distribution*: Separate copies of the same data need to be sent via multiple iBSs to the same MS.

- *Data content synchronization*: Pieces of data arriving at the mobile station at the same time from different base stations should be copies of the same data for the mobile station's radio system to correctly combine the pieces into a single copy.

Section 2 examines the new challenges for realizing soft handoff in all-IP wireless networks and Section 3 describes and analyzes the proposed new solutions.

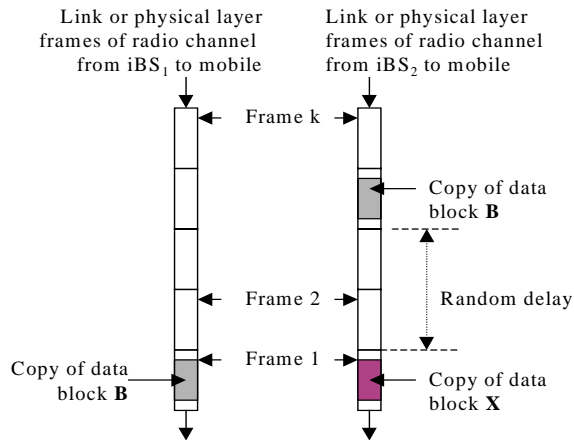
## 2 Challenges for Realizing Soft Handoff in All-IP Wireless Networks

In today's circuit switched CDMA networks such as IS-95[2], a centralized Selection and Distribution Unit (SDU) is responsible for data distribution in the forward direction (from BS to MS). The SDU creates and distributes multiple streams of the same data over layer-2 circuits to multiple BSs that in turn relay the data to the MS. The MS's radio system (typically working below the IP layer) collaborates with the BSs to synchronize the radio channel frames and combine the radio signals received from different BSs to generate a single final copy of received data. The SDU helps ensure data content synchronization by ensuring that the matching layer-2 frames sent to different base stations contain copies of the same data. In the reverse direction (from MS to BS), the MS ensures that the matching layer-2 frames sent to different BSs contain copies of the same data. The SDU then selects one of the frames received from different base stations as the final copy of the data.

Achieving soft handoff among distributed iBSs introduces several new technical problems that cannot be solved readily by the mechanisms developed for today's centralized circuit-switched wireless networks.

The first key problem is loss of data content synchronization. With distributed iBSs, centralized control entities, such as the SDU in circuit switched wireless networks, will no longer exist. Consequently, even though the CDMA radio system is capable of synchronizing the link and physical layer frames on the radio channel, it cannot, on its own, guarantee that the matching frames from different base stations will carry copies of the same data. For example, IP packets can be lost on their way to the MS, creating random gaps in the packet streams received by the MS from different iBSs. Furthermore, copies of the same data may arrive at the MS at different times due to the random delays suffered

by the packets. Random gaps and delays can lead to a loss of data content synchronization as illustrated in Figure 1. Suppose that packet X is lost at BS<sub>1</sub> (due to, for example, buffer overflow) but is not lost at BS<sub>2</sub>. Packet B from BS<sub>1</sub> and packet X from BS<sub>2</sub> may arrive at the MS at the same time and the MS's radio system will not be able to tell that they are not copies of the same data and will hence erroneously combine B with X.



**Figure 1: Loss of data content synchronization.**

Today's approaches to iBS design make it even more difficult to implement soft handoff. For example, a typical way of designing an iBS is to add (or connect) radio transmission and receiving equipment for one cell directly onto an interface of a standard IP router. Such a design forces the MSs in different cells to be on different IP subnets. Otherwise, suppose MSs in two cells belong to the same IP subnet *S*. Then, the iBSs (IP routers) for both cells will advertise to other IP routers that they can reach *all* the hosts on subnet *S*. However, each iBS can only reach a subset of the hosts on subnet *S* (i.e., the set of hosts currently served by the iBS). This means that other routers will not be able to determine which iBS should receive a packet destined to a host on subnet *S*. In other words, packets may be delivered to the wrong iBS and consequently cannot reach the destined host.

The fact that MSs in different cells belong to different IP subnets suggests that an MS may have to change its IP address *every time* it moves into a new cell. Changing IP address usually takes a long time using today's methods for dynamic IP address assignment (e.g., DHCP(RFC2131)). Having to change IP addresses when moving from one cell to another also makes soft handoff more difficult to implement. For example, if an MS has to use different IP addresses to receive IP packets from different iBSs, IP packets coming to the MS from different iBSs will not be identical because they carry different IP destination addresses. Consequently, copies

of the same packets from different base stations may not be correctly combined by the MS's radio system.

Recently, methods (e.g., HAWAII, Cellular IP) have been proposed to enable MSs to move within a domain of multiple IP subnets without having to change their IP addresses. These methods, however, typically require complex IP-layer signaling and significant changes to the IP routers in the domain. Furthermore, these methods have not considered how to solve the data content synchronization problem.

Another problem is how to distribute multiple streams of the same data via different iBSs to the same MS. Today's techniques typically require complex IP-layer signaling and control mechanisms. For example, IP multicast may be used. However, implementing IP multicast is complex and IP multicast may require an MS to use multiple IP addresses simultaneously during soft handoff. Furthermore, IP multicast may cause packets to be sent to MSs that are not the intended destination of the packets, wasting valuable resources in the wireless network and on the MS (e.g., power).

### 3 Distributed Soft Handoff for All-IP Wireless Networks

This paper proposes a novel approach for soft handoff between iBSs. The proposed approach does not impose any change to the protocols, software and hardware used by MSs. An MS can use existing radio technologies (e.g., RAKE receivers) to perform signal combination for soft handoff and existing standard IP-layer protocols for IP-layer signaling and data transport.

The proposed approach uses a concept referred to as *Shadow Addresses* to realize data distribution. This approach requires little signaling at any protocol layer and does not require IP packets to be broadcast over the air. Shadow Addresses also allow MSs served by multiple iBSs to be on the same IP subnet, therefore reducing the frequency at which MSs have to change their IP addresses when moving into new cells. The proposed approach ensures data content synchronization at the MS by a novel IP-layer procedure performed on and only on the iBSs.

Section 3.1 describes the concept and sample applications of shadow address, including using shadow addresses to support data distribution and to enhance the design of iBSs. Section 3.2 describes and analyzes the proposed data content synchronization approach.

#### 3.1 Data Distribution Using Shadow Addresses

This section proposes a concept referred to as *Shadow Addresses* that will allow 1) MSs served by multiple iBSs to be on the same IP subnet and 2) multiple streams of the same data to be distributed via multiple iBSs to the

MS with little signaling and without broadcasting IP packets to MSs and iBSs that are not the intended destinations or proxies of the packets. This section describes the concept and sample applications of shadow addresses within a single IP subnet while the same concept and applications can be extended to across multiple IP subnets.

Consider multiple iBSs interconnected via a wireline IP subnet. When a device (e.g., IP host, router or iBS) on the wireline IP subnet wants to send an IP packet to a MS, the sending device will have to determine what layer-2 address (e.g., what MAC address when the wireline subnet is an Ethernet) to use to send the packet over the wireline subnet. The layer-2 protocol and addresses used in the wireline network are most likely different from the wireless layer-2 protocol and address (e.g., this will be the case when the radio system is based on cdma2000 [3] or W-CDMA [3]). In such cases, the sending device cannot use the layer-2 address of the MS to send layer-2 frames over the wireline IP subnet.

To ensure that a sender on the wireline network can direct the packet to the right iBS, a unique *wireline* layer-2 address will be assigned to each MS. This *wireline* layer-2 address can be viewed as the MS's "shadow" on the *wireline* layer 2 and will therefore be referred to as the layer-2 *shadow address* of the MS. The shadow address for an MS may be assigned dynamically or configured statically. The shadow addresses are used solely by the iBSs; MSs do not necessarily need to be aware of their shadow addresses.

An iBS uses shadow addresses to determine which layer-2 frames arriving from the wireline network should be accepted for further processing at the IP layer (e.g., packet forwarding, QoS control). For this purpose, each iBS maintains a *Watch List* of the shadow addresses of all the MSs currently served by the iBS. The wireline interface of the iBS will monitor the layer-2 frames from the wireline network and will accept any layer-2 frame whose destination layer-2 address matches a shadow address in the iBS's *Watch List*. The IP packet carried in an accepted layer-2 frame will be sent to the IP layer for further processing.

When a device on the local wireline IP subnet wants to send IP packets to an MS, the sending device will first determine the shadow address of the MS. The sending device can do so, for example, using the Address Resolution Protocol (ARP (RFC 826)). In particular, it will broadcast an ARP REQUEST packet over the local wireline IP subnet. The iBS that has the shadow address of the destination MS in its *Watch List* will respond to the ARP request with the shadow address of the MS. The shadow address will then be used by the sending device on the local IP wireline network to send layer-2 frames containing the IP packets to the correct iBS. When the

shadow address of an MS is in the *Watch Lists* of multiple iBSs, all these iBSs may respond to the ARP request. These responses will contain the same shadow address of the destination MS. The sending device can ignore the extra responses to the ARP requests.

iBSs using shadow addresses do not have to run IP routing protocols (e.g., OSPF or BGP). Instead, an iBS can easily build up and maintain its local IP packet forwarding table (e.g., the *Watch List* and the outgoing port for each local MS) using local information and the shadow addresses of the MSs being served by the iBS.

As shown in

Figure 2, when mobile station  $MS_x$  first starts communication with a new iBS ( $iBS_B$ ), the new iBS may obtain the MS's shadow address  $MAC_x$  from the previous iBS ( $iBS_A$ ). Alternatively, the new iBS may obtain the MS's shadow address from the MS itself when mobiles help carry their shadow addresses. The new iBS will insert  $MAC_x$  into its *Watch List* and start accepting layer-2 frames coming from the wireline network that carries  $MAC_x$  as destination layer-2 address and will send the packets carried in these frames to the IP layer on the iBS for further processing. Since both iBSs have  $MAC_x$  in their *Watch Lists* now, they will both start accepting layer-2 frames destined to  $MAC_x$  and forwarding the IP packets in the frames to the mobile simultaneously.

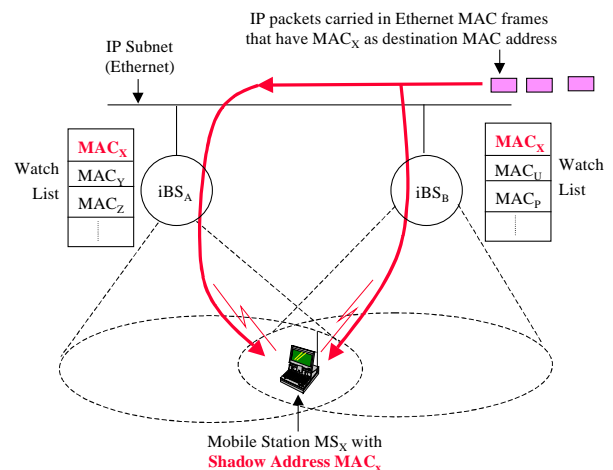


Figure 2: Data distribution using shadow addresses.

### 3.2 Data Content Synchronization

One way to achieve data content synchronization at an MS is to have all iBSs transmit copies of the same IP packet to the MS at precisely the same time. However, scheduling and synchronizing the precise packet

transmission times on different IP devices (in this case, iBSs) are often difficult in a real IP network.

This section describes a new IP-layer procedure performed by *iBSs* to ensure that the data arriving at the *MS* at the same time from multiple *iBSs* are copies of the same data. The method is an IP-layer procedure and is therefore independent of link layer protocols used in the radio system. The procedure is performed by *iBSs* rather than by the *MSs* and therefore avoids any modification to the *MS*. Section 3.2.1 describes the proposed method and Section 3.2.2 analyzes its re-synchronize delay, i.e., the latency of regaining data content synchronization after synchronization is broken.

### 3.2.1 Data Content Synchronization Method

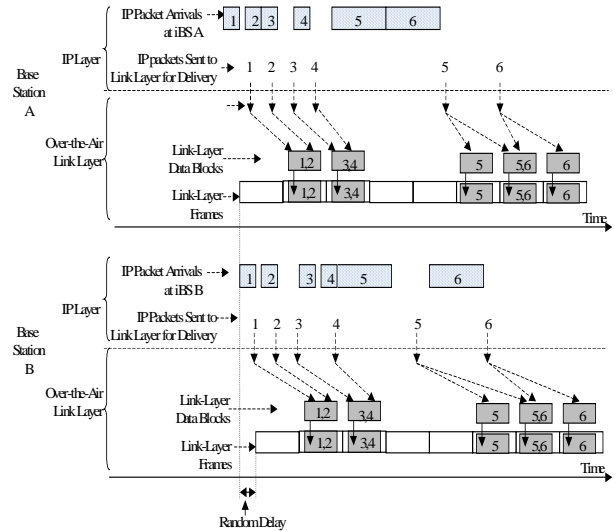
Rather than trying to schedule the precise timing for simultaneous packet transmissions on multiple *iBSs*, the proposed method seeks to ensure that the streams of layer-2 data blocks sent by multiple *iBSs* to the *MS* are *matchable streams*. Matchable streams are streams of layer-2 blocks (or more precisely, the physical layer data resulting from these blocks) that can be correctly matched and combined by the *MS* using today's radio technologies (e.g., RAKE receivers). Suppose that the streams of IP packets sent by different *iBSs* to an *MS* have either no gaps (i.e., missing IP packets) or identical gaps. Then, the layer-2 data block streams from the *k*<sup>th</sup> *iBSs* to the *MS* will be matchable if, for any *k*, the *k*<sup>th</sup> layer-2 data block sent by both *iBSs* to the *MS* contains the same amount of payload (i.e., have the same length). The *matching layer-2 data blocks* (i.e., data blocks that are copies of the same data) from different *iBSs* do not have to arrive at the mobile at precisely the same time. The mobile's radio system can synchronize these data blocks using today's radio channel synchronization techniques, as long as the delay jitters are not excessively large.

It is also important to note that generating matchable streams of layer-2 data blocks do not require each *iBS* to send copies of the same IP packet to the layer-2 protocol at precisely the same time for delivery to the *MS*. Furthermore, matchable streams of layer-2 data blocks can be generated by performing only IP-layer processing on the *iBSs* alone. Figure 3 illustrates how matchable streams of layer-2 data blocks can be generated when the IP packets are sent by different *iBSs* to the layer-2 protocol on their radio interfaces at different times for delivery to the *MS*. A number *x* inside a layer-2 data block or layer-2 frame indicates that the data block or the layer-2 frame contains data from the IP packet with sequence number *x*.

1) Based on the observations described above, a *basic data content synchronization procedure* can be as

follows (we will use the Radio Link Protocol or RLP as an example radio layer-2 protocol in the following discussions). Starting from the delivery of the copies of the same IP packet to the *MS*, each *iBS* will Use RLP frames of identical length,

- 2) Deliver only fully filled RLP frames to the *MS* unless
  - a) A timer  $T_p$  expires, or
  - b) Instructed by the upper layer (i.e., the IP layer) to send the current data.



**Figure 3: iBSs do not send to send IP packets at precisely the same times.**

In real networks, several events may cause a loss of data content synchronization when the above method is used. For example, gaps may randomly occur in the IP packet streams sent by different *iBSs* to the mobile as discussed in Section 2. Also, when timer  $T_p$  expires or when the IP layers on different *iBSs* instruct their layer 2 to send the current available data, the resulting layer-2 data blocks from different *iBSs* may not contain an identical amount of payload.

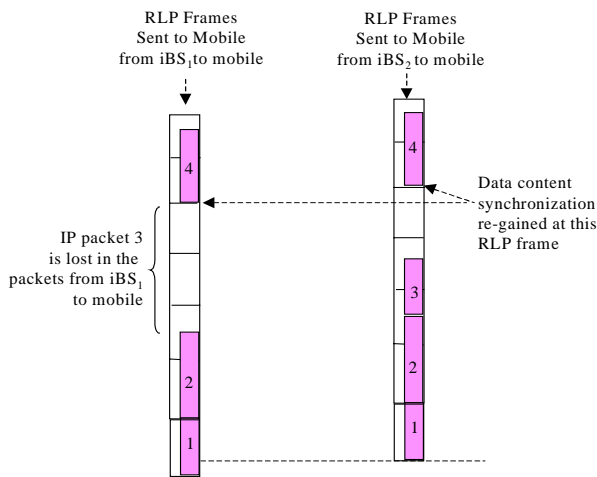
Next, we describe a method for re-gaining data content synchronization each time data content synchronization may be lost. The basic idea is that whenever an event occurs that may cause a loss of data content synchronization, the *iBS* that first detects the event will negotiate with the other *iBSs* involved in the soft handoff procedure to restart synchronization from a new IP packet. In particular, the *iBS* will select a new IP packet that they have not yet sent to the *MS* and re-start the basic data content synchronization procedure described above starting from that packet. Without loss of generality, we next describe the data content re-

synchronization procedure using packet gaps as the cause of loss of data content synchronization.

Suppose that  $iBS_1$  detects a gap between packet  $k$  and packet  $m$  ( $m > k$ ) in the stream of IP packets destined to the MS. That is,  $iBS_1$  has received packets  $k$  and  $m$  but has not received any packet between packets  $k$  and  $m$ .  $iBS_1$  will initiate the following *data content re-synchronization procedure*:

- It selects a packet  $q$  ( $q \geq m$ ) and requests  $iBS_2$  to start re-synchronization starting at packet  $q$ .
- It sends immediately to the MS *all* the packets that it has received before packet  $q$ .
- It halts the delivery to the MS of packet  $q$  and the packets arrived at  $iBS_1$  after packet  $q$ .
- If  $iBS_2$  knows it can (or has a high level of confidence that it can) re-start data synchronization as requested by  $iBS_1$  (e.g., when  $iBS_2$  has received packet  $q$  and has not yet sent it to the MS, or has not yet received packet  $q$ ),  $iBS_2$  will positively acknowledge  $iBS_1$ 's request. Then,  $iBS_2$  will send immediately to the MS all the packets  $iBS_2$  receives before packet  $q$ . Starting from packet  $q$ ,  $iBS_2$  will restart the basic data content synchronization procedure.
- Upon receiving the positive acknowledge from  $iBS_2$ ,  $iBS_1$  will restart the basic data content synchronization procedure at packet  $q$ .

Figure 4 shows the time sequences of the RLP frames sent by two  $iBS$ s to a MS when loss of data content synchronization (caused by a gap in the IP packet stream) is recovered using the re-synchronization procedure.



**Figure 4: Data content re-synchronization.**

Some times,  $iBS_2$  may not be able to start re-synchronization as requested by  $iBS_1$ . For example,  $iBS_2$  may have already sent packet  $q$  to the MS. Or,  $iBS_2$  may have already known that packet  $q$  is missing in the stream

of IP packets it received. In such cases,  $iBS_2$  will select a new packet  $p$  after packet  $q$  ( $p > q$ ) that it has not yet sent to the mobile and requests  $iBS_1$  to start re-synchronization at packet  $p$ . The re-synchronization process continues until it is successful. Since packet loss is rare in a well-designed wireline IP networks used to interconnect  $iBS$ s, the proposed data content re-synchronization can expect to converge quickly. Section 3.2.2 quantifies the performance of the re-synchronization procedure in terms of success probability and the time it takes to re-gain data content synchronization.

The re-synchronization procedure described above can be used to re-gain data content synchronization when loss of data content synchronization is caused by other events besides gaps in IP packet streams. If, for example,  $T_p$  on  $iBS_2$  expires before a RLP frame is fully filled,  $iBS_2$  will send the partially filled frame to the MS. However, this may lead to loss of data content synchronization at the MS. To re-gain data content synchronization,  $iBS_2$  can select a packet that it has not yet sent to the MS and request  $iBS_1$  to start the same data content re-synchronization procedure described above.

IP packet retransmissions by the data sources will not cause a loss of data content synchronization. This is because such retransmitted packets will be in the same sequential positions in the packet stream routed to every  $iBS$ . Retransmissions of IP packets by the  $iBS$ s, however, may lead to a loss of data content synchronization at the MS. This is because each  $iBS$  may insert a re-transmitted IP packet at a different sequential position in the streams of packets they send to the MS. However,  $iBS$ s typically will not retransmit IP packets. In the rare cases where an  $iBS$  needs to retransmit an IP packet, it can initiate the re-synchronization procedure described above.

To reduce the impact of loss of data content synchronization caused by unexpected events, the  $iBS$ s currently involved in soft handoff may periodically restart the data content re-synchronization procedure.

### 3.2.2 Performance Analysis

This section shows how to choose the packet to start the re-synchronization process so that the probability of successful re-synchronization satisfies pre-determined criteria. We also analyze the latency of data content re-synchronization.

We consider two  $iBS$ s ( $iBS_1$  and  $iBS_2$ ) that are performing soft handoff for a mobile  $MS_x$ . For ease of illustration, we assume in the analysis that IP packet gaps are the cause of loss of data content synchronization. The same analysis applies to other causes of loss of data content synchronization. Suppose that, at time  $t$ ,  $iBS_1$  detects a gap between packets  $k$  and  $m$  ( $m > k$ ) in the IP

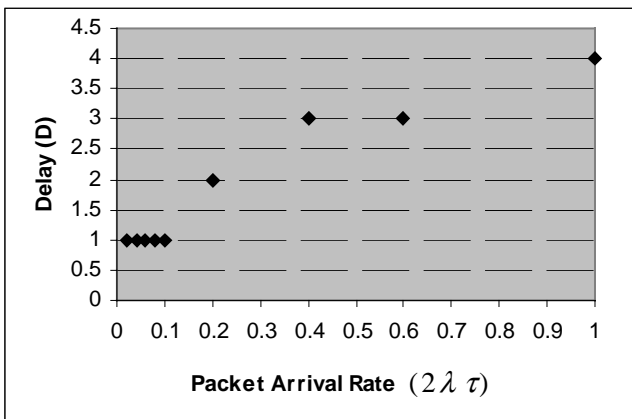
packet stream destined to  $MS_X$ . Assume further that  $iBS_1$  will send a re-synchronization request to  $iBS_2$  immediately after detecting the gap.

We derive the probability  $P$  of successful re-synchronization if  $iBS_1$  asks  $iBS_2$  to re-synchronize at IP packet  $q$  ( $q \geq m$ ). Since packet  $m$  arrives at  $iBS_1$  at time  $t$ , it will arrive at  $iBS_2$  no earlier than  $t - \tau$ , where  $\tau$  is the time it takes for a packet to travel from one  $iBS$  to another on the local wireline subnet connecting the  $iBS$ s. It takes  $\tau$  time for the re-synchronization request to travel from  $iBS_1$  to  $iBS_2$ . Therefore, the probability of successful re-synchronization will be at least as large as the probability that the re-synchronization request reaches  $iBS_2$  before packet  $q$  and that packet  $q$  will not be lost on its way to  $iBS_2$ . Assume that the arrivals of IP packets (destined to mobile  $MS_X$ ) at each  $iBS$  follow a Poisson process with an average arrival rate of  $\lambda$  packets per second. Then, we have

$$P \geq P_b \sum_{n=0}^D \frac{(2\lambda\tau)^n e^{-2\lambda\tau}}{n!} \quad (1)$$

where  $P_b$  is the probability that IP packet  $q$  is not lost before arriving at  $iBS_2$ .

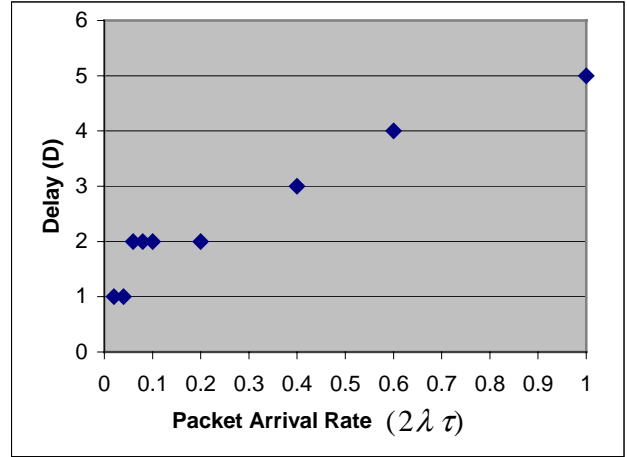
Next we analyze the re-synchronization delay as represented by  $D=q-m$ . Figure 5 and Figure 6 show the re-synchronization delay  $D$  vs. packet arrival rates for target successful re-synchronization probabilities (in a single try) of 99.5% and 99.9% respectively. Both figures assume that  $P_b=1$ . We observe that, with high probability ( $>99.5\%$ ), the proposed method can re-gain data content synchronization within a small number of packet arrival times, even if the data arrival rate is high (i.e.,  $2\lambda\tau = 1$ ).



**Figure 5: Re-synchronization delay vs. packet arrival rate (target success probability = 99.5%).**

As discussed previously, the proposed procedure can also be used as a precaution to prevent loss of data

content synchronization due to unexpected events. When used as a precaution and it turns out that there is no loss of data content synchronization, the proposed re-synchronization procedure will not introduce any packet delay if  $\Delta T_q > 2\tau$ . Here,  $\Delta T_q$  is the time interval between the time at which  $iBS_1$  starts the re-synchronization



procedure and the time packet  $q$  arrives at  $iBS_1$ .

**Figure 6: Re-synchronization delay vs. packet arrival rates (target success probability = 99.9%).**

#### 4 Summary

IP packet distribution and data content synchronization are two key issues to be addressed to enable soft handoff in all-IP networks. This paper presented the concept of Shadow Addresses and showed how it can be used to realize data content synchronization in such networks. Shadow address allows IP packet distribution via multiple IP-based base stations to a mobile with simple and minimal signaling. The paper also presented a novel IP-layer procedure performed only on  $iBS$ s for achieving data content synchronization without imposing any modification to a mobile station's radio system.

#### 5 References

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