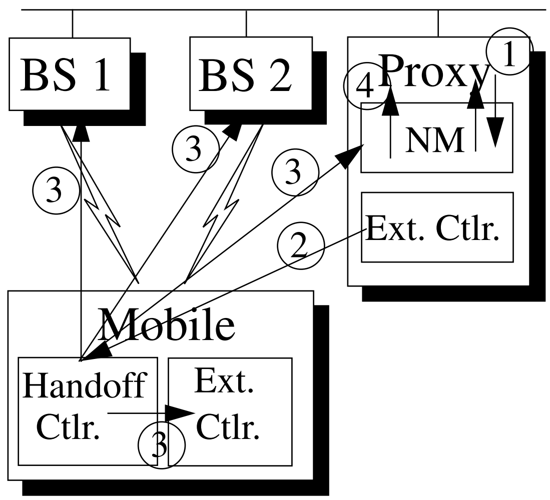

FIGURE 4. Vertical Handoff Due to Load Balancing.

7.4 Automatic Vertical Handoff Due to Load Balancing (Figure 4)

The Proxy requests measurements from the Network Monitor and finds that the 99% of the available bandwidth on the 915 Mhz wavelan is being used, while only 20% of the available bandwidth on the 2.4Ghz wavelan is being used. It determines that the 2.4Ghz wavelan should be used, and the External Controller on the Proxy sends an advice message to the Handoff Controller, telling it to switch to the 2.4Ghz Wavelan network. The Handoff Controller performs the same operations as in the user-assisted vertical handoff case.

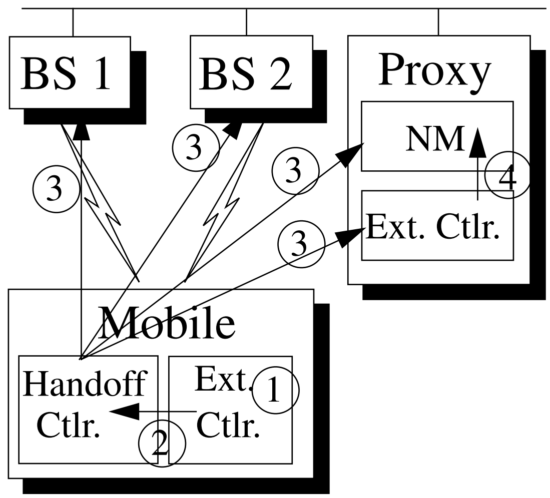

FIGURE 3. User-Assisted Vertical Handoff.

7.2 User-Assisted Vertical Handoff (Figure 3)

In the middle of a demo, the user clicks the switch-to-metricom-network button on the Tcl/Tk program. The subset of the program that is the External Controller sends a message to the Handoff Controller, telling it to switch to the metricom network. The controller brings up the Metricom interface, registers with the Metricom base stations, and unregisters with the Wavelan base Stations and shuts down the Wavelan interface. It also sends a **list-active-network-reply** message to any other External Controllers and the Network Monitor. If callbacks were registered and are triggered, the NM sends a message to the proxy, who changes the amount of distillation that it does.

7.3 Automatic Vertical Handoff Due to Mobility (Figure 2)

The Handoff Controller requests measurements from the Network Monitor and finds that no beacons in the last 15 seconds have been received from the Wavelan network. It determines that the Wavelan network must be down, and the Handoff Controller performs the same operations as in the user-assisted vertical handoff case.

- **register-latency-morethan:**
- **register-latency-lessthan:**
- **register-per-lessthan:**
- **register-per-morethan:**

6.7 Naming Conventions

The name for a network will be the same as its UNIX interface name. The name for a base station will be its IP address as a single word with bytes in network order.

7.0 Sample Scenarios

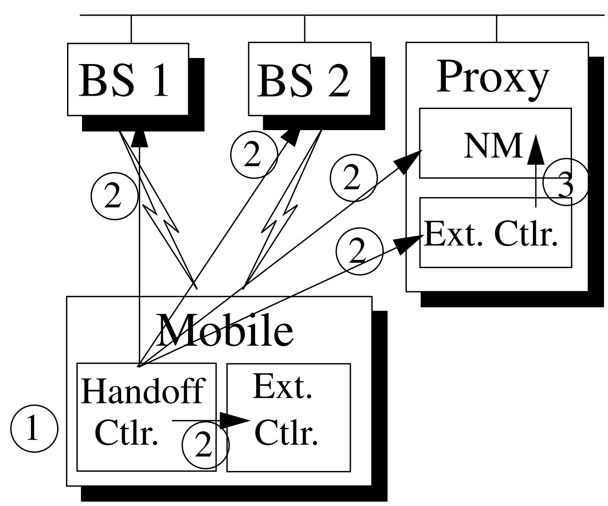

FIGURE 2. Horizontal and Vertical handoff due to mobility.

7.1 Horizontal Handoff (Figure 2)

The Handoff Controller receives beacon packets and finds that the signal strength of one base station is greater than the currently active base station. The controller sends a **list-active-basestation-reply** message to the external controller (if any) and Network Monitor. This new base station happens to have less bandwidth available per client (in fact, enough to trigger a previously registered **register-bandwidth-lessthan** event) so the Network Monitor also sends a message to the Proxy who changes the amount of distillation that it does.

All measurements should be taken right at the gateway to the application, that is, not counting any headers and including all layer processing overhead.

All measurements will also include confidence intervals.

Network dependent messages:

- **whatis-best-latency**: Lowest latency ever seen by a single user.
- **whatis-current-per**: Returns the current packet error rate.
- **whatis-best-bandwidth**: best observed bandwidth ever seen by a single user. This should indicate the cost of layer processing and headers.

A subset of the network dependent parameters actually never change. These are:

- **whatis-power-tosend(y)**: Return the function used to estimate the power cost in watts to send “chunks” of various sizes using protocol y.
- **whatis-power-torecv(y)**: Returns the function used to estimate the power cost in watts to receive “chunks” of various sizes using protocol y.
- **whatis-cost-tosend(y)**: Return the function used to estimate the dollar cost (in cents) to send “chunks” of various sizes using protocol y.
- **whatis-cost-torecv(y)**: Return the function used to estimate the dollar cost (in cents) to receive “chunks” of various sizes using protocol y.

  One important thing to note is that although these functions are only sent from the Network Monitor to the requestor only once, the functions depend on parameters that must be updated periodically (for example, the power cost to send a chunk of b bytes is dominated by the time to complete the transfer, which in turn depends on the current observed bandwidth of the network). It is the responsibility of the requestor of the function to also request the parameters that the function uses.
- **whatis-power-turnon**: Return the power cost to turn the network interface on.
- **whatis-power-turnoff:** Return the power cost to turn the network interface off.
- **whatis-max-packetsize(y)**: Returns the maximum packet size supported by the protocol y.
- **whatis-max-packetsize(y):** Returns the “optimal” packet size supported by the protocol y. This will usually be the packet size of the underlying wireless medium.

  The packet size parameters will be used by the proxy to determine the best chunk size for the connection between the Proxy and mobile.

6.6 Workload dependent:

- **whatis-current-bandwidth**: We will use averaging over time on this.
- **whatis-current-latency:** Averaging over time on this too.

The Network Monitor can also register callbacks for certain events. The network will send back a message when the event is true:

- **register-bandwidth-lessthan:**
- **register-bandwidth-morethan:**

- **use-any-basestation**: Feel free to switch to new basestations at will.
- **don't-use-this-network**: Use any network but this one, unless it is the only one available. Cancelled by a **use-any-network** message.

6.4 Handoff Controller Messages:

In addition, the external controller can query certain things of the Handoff Controller in order to maintain its own state (This allows the External Controller to come up and down at will):

- **list-all-networks**: Returns a list of all networks that the Handoff Controller knows about.
- **list-active-networks**: Returns the currently active networks. An active network is defined as a network that is currently receiving beacons.
- **list-all-basestations**: Returns a list of all known basestations for the currently active network(s).
- **list-active-basestations**: Returns a list of the currently active basestations for the currently active network(s). An active network is defined as a network that is currently receiving beacons.
- **list-used-network**: If a **use-this-network** message has been received and is currently being used(i.e., the mobile hasn't moved out of range of that network), return that network.
- **list-used-basestation**: If a **use-this-basestation** message has been received and is currently being used(i.e. the mobile hasn't moved out of range of that basestation), return that basestation.
- **list-dontuse-networks**: Returns a list of all networks that are available but are marked as "don't use".
- **list-dontuse-basestations**: Returns a list of all basestations that are available but are marked as "don't use".

The Handoff Controller can also originate the following messages without being queried by the External Controller/Proxy:

- **list-active-network-reply**: This looks identical to a reply to a **list-active-network** message.
- **list-active-basestation-reply**: This looks identical to a reply to a **list-active-basestation** message.
- **disconnected-network**: No basestations for any network are reachable. This would probably be used by the client-side Gimpy library as an escape hatch.

6.5 Network Monitor Messages

The following messages are a function of the different networks(e.g don't vary as a function of workaday).

5.0 High level goals that these components should satisfy

1. Portability: All communications should be message based via sockets. This allows components to move (within the limits presented above).
2. Unreliability of components: Any component can die without any other component dying.
3. Unreliability of messages: Any message can be lost. If you want reliability, roll your own.
4. Low overhead: Try to avoid sending messages over the wireless link as much as possible; the bandwidth on these devices can be a precious resource, and single packets can affect streams of data more than one would think(i.e. Wavelans and any half-duplex device).

6.0 Messaging between the components

6.1 Connection model

All communication is done via point-to-point UDP connections. No multicasting, though we may need to revisit this later if scalability becomes a problem.

6.2 Beacon Packets

Currently, beacon packets only include the base station identifier. Device drivers on the mobile sample the signal strength and quality of these beacon packets and use this information when making handoff decisions. In the future, the beacon packets may also include hints such as “nearby networks”. For example, a Wavelan base station near the entrance of a building would indicate that Metricom is a “nearby” network. This allows the mobile to hide the latency of network registration from the user. They may also include snapshots of the Network Monitor’s collected statistics, which it can to use to inform the mobile of network conditions (albeit at a coarser granularity than the proxy).

6.3 External Controller Messages

The kinds of advice that an external controller can give are:

- **use-this-network**: Switch to this network if it is available. Do not switch from this network to any other network until receiving an **use-any-network** message or if the specified network becomes unreachable. This message is cancelled by a **use-any-network** message or a **use-any-basestation** message where the basestation is of a different network than the currently “used” network.
- **use-any-network**: Feel free to switch to new networks at will.
- **use-this-basestation**: Switch to this base station if it is available. Do not switch from this basestation to any other basestation until receiving an **use-any-basestation** message or if the specified basestation becomes unreachable. This message is cancelled by a **use-any-basestation** message or by a **use-any-network** message.
- **dont-use-this-basestation**: Use any basestation but this one, unless it is the only one available. Cancelled by a **use-any-basestation** message.

It can also take as input *advice* from an External Controller, which it uses while making handoff decisions.

3.3 External Controller

The External Controller serves two purposes: (1) To act as a tool for user-assisted handoff, and (2) to allow the user or Proxy to provide advice in making handoff decisions.

There are currently two types of External controllers:

- (Some subset of) a Tcl/Tk program that will display network characteristics. A part of this program will include an external controller.
- A text-based shell.

3.4 Who lives where.

This will describe the ideal location of the location of each component, in terms of **SHOULD** or **MUST**.

The Network Monitor **SHOULD** live at the Proxy. The reason that the Network Monitor should live at the Proxy rather than at the mobile is that the Network Monitor can more accurately measure the per-user bandwidth than any single mobile, and that in some cases(i.e. the mobile is a PDA), the mobile does not have the resources it needs to support a Network Monitor. The reason that the Network Monitor should live at the Proxy rather than at the base station is that the Proxy accurately represents the end-to-end connection used for distillation. Note that in some cases, the bandwidth between the Proxy and the base station may be less than the bandwidth between the base station and the mobile device(i.e. when the Proxy is in the mobile's home domain and the mobile is roaming in some far away domain).

The Handoff Controller **MUST** live at the mobile. This is because when the mobile moves from one base station or network to another, it will become disconnected from the unit that is making routing decisions. This is a problem that was encountered in the Infopad system.

The External Controller can live anywhere. A copy can live at the Proxy, and the Proxy can generate advice messages when switching networks or base stations would be ideal for load balancing purposes.

4.0 Reasons to Hand Off

It is important to make the distinction between handoffs due to mobility and handoffs due to changing network conditions. The Handoff Controller is only concerned with handoffs due to mobility; that is, the signal quality, presence, or pattern of a mobile's movement. The External Controller at the Proxy is concerned with handoffs due to changing network conditions, for load balancing or fairness reasons. The External Controller at the mobile is a way for the user to make choices that a normal application might not be able to make (for example, using Metricom--which has its own battery--instead of Wavelan when battery power is low).

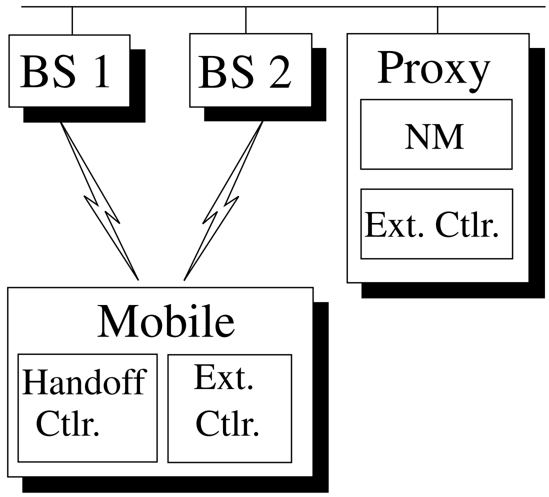

FIGURE 1. The components of vertical handoff and their locations.

3.1 Network Monitor

This component makes all measurements having to do with network interfaces. This component does the statistical modeling of each network interface, and collects statistics having to do with the quality of the connections between the Proxy and the mobile over the various wireless networks.

The specific characteristics that the network monitor will keep are:

- Round trip latency to the proxy.
- Best-ever latency from the mobile to the proxy
- Current aggregate bandwidth from the mobile to the proxy.
- Best-ever aggregate bandwidth from the mobile to the proxy.
- Average per-user bandwidth from the mobile to the proxy.
- Cost (in power and cents) to send a chunk.
- The class (in the CBQ sense) of the mobile.

3.2 Handoff Controller

This component makes the decision of when to make horizontal and vertical handoffs. It receives beacon packets to determine the quality of each interface and the relative proximity of each base station, and sends encapsulation/decapsulation messages to base stations (in the case of horizontal handoff), and powers up and down network interfaces (in the case of vertical handoff).

Network Monitoring and Handoff in Daedalus

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This document outlines the roles of and communications between the parts of Daedalus that take part in Horizontal/Vertical Handoff.

1.0 Vertical vs. Horizontal Handoff

Vertical handoff is between base stations of different networks, horizontal handoff is between base stations of the same network.

2.0 Internal vs. External Base Stations

Internal base stations are ones over which we have control(i.e. Wavelan). External base stations are ones over which we have no control(i.e CDPD). The important thing is that some low-level physical measurements may be impossible from external base stations, which may make handoffs due to mobility more difficult.

3.0 The Components

The Network Monitor and Handoff Controller are currently together as vrouted.