Interactive Visualization and Analysis of Network and Sensor Data on Mobile Devices

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Abstract

Mobile devices are rapidly gaining popularity due to their small size and their wide range of functionality. With the constant improvement in wireless network access, they are an attractive option not only for day to day use, but also for in-field analytics by first responders in wide spread areas. However, their limited processing, display, graphics and power resources pose a major challenge in developing effective applications. Nevertheless, they are vital for rapid decision making in emergencies when combined with appropriate analysis tools.

In this paper, we present an efficient, interactive visual analytic system using a PDA to visualize network information from Purdue's Ross-Ade Stadium during football games as an example of in-field data analytics combined with text and video analysis. With our system, we can monitor the distribution of attendees with mobile devices throughout the stadium through their access of information and association/disassociation from wireless access points, enabling the detection of crowd movement and event activity. Through correlative visualization and analysis of synchronized video (instant replay video) and text information (play statistics) with the network activity, we can provide insightful information to network monitoring personnel, safety personnel and analysts. This work provides a demonstration and testbed for mobile sensor analytics that will help to improve network performance and provide safety personnel with information for better emergency planning and guidance.

Keywords: mobile visualization, network visualization, visual analytics

Index Terms: I.3.2 [Computer Graphics]: Graphics Systems—Network Graphics; I.3.8 [Computer Graphics]: Applications—Visual Analytics

1 Introduction

Mobile devices are becoming ubiquitous in our high-tech society. As such, technological advances are occurring at an increasing rate, enabling advanced information processing capabilities on such devices. Advances in processor clock rate, graphics capabilities, wireless networking, and low-power designs have increased the potential for detailed analysis using mobile devices.

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Simultaneously, the quantity of data available for analysis is steadily increasing, requiring improved processing tools in order to quickly access and evaluate information. In some situations, it is desirable or necessary to process this information on site and, as a result, mobile devices provide a critical solution to in-field data analysis.

Management of sensor and network data is one area that benefits from in-field analysis. Wireless networks pose a challenge in extracting relevant connectivity information for issues such as network diagnostics and load balancing, while sensor networks pose similar problems. Additionally, as sensor technology advances, the quantity of data increases, and methods need to be developed to allow in-field visual analysis of large data streams.

In-field analysis can also be beneficial to the analysis of social behavior based on situational stimuli. Sporting events are an excellent test area for such analysis, as there are many issues that arise in the effective production of such events. For example, the sheer quantity of attendees may require additional considerations with respect to emergency situations and general crowd control. Also, event organizers can benefit from exploratory data analysis in order to improve their services and to increase customer satisfaction.

It should be noted that data from seemingly unrelated sources can often be used to better analyze some types of situational characteristics. One such method is the analysis of network data to determine crowd activity and interactions. By examining connectivity information in a wireless network, we can extract cues not only on network issues, but also on how users react in certain situations. Thus, the same information that we use to improve network performance could potentially be used for crowd-guidance situations.

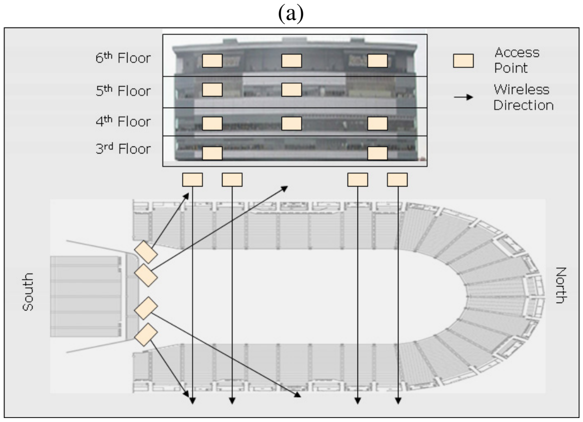
Our work is best described as "visual analytics." Visual analytics is defined as "the science of analytical reasoning facilitated by interactive visual interfaces" [21]. More specifically, the integration of mobile devices into the analytical process is referred to as "mobile analytics." Using state-of-the-art mobile devices, we can enhance the analytical process through interactive, integrated data analysis and visualization, enabling the user to extract important features necessary for rapid, actionable decision making on site.

However, the capabilities of mobile devices are not without their limits. Low screen resolution, such as 240 x 320, prevents large amounts of data from being displayed on screen. Power considerations prevent large storage capacities on the device, as well as severely limiting display and network capabilities. These limitations drive us to incorporate compact (but detailed) analysis, correlation and visualization techniques through which complex information can be clearly conveyed.

We must also be aware of issues in data uncertainty and confidence. In many cases, using a combination of data sources can help to resolve ambiguities. Multi-modal fusion and synchronized multiple information techniques can be of great use in the prompt, accurate analysis of input data.

In this paper, we utilize information from Purdue's Ross-Ade

(a)



(b)

Figure 1: (a) Aerial view of Purdue's Ross-Ade Stadium. (b) Access point layout in the stadium. This figure shows 18 of the 20 access points in the visualization, that are typically accessed by users. Eight are installed outside (four near the south score board and the other four on the west side) and the remaining ten are inside the pavilion on the third, fourth, fifth and sixth floors as shown above.

Stadium during football games as a testbed. Figure 1 shows an aerial view of Ross-Ade Stadium at Purdue and the *eStadium* access point (AP) layout in the stadium. Figure 2 shows the wireless coverage area of all the APs in the stadium, some of which overlap. Wireless network access information is collected through these APs. We use these network logs, along with the related video and text data, to display various visualizations synchronized with time. Through the combined visualization and analysis of video and text data, we can gain insight into network performance and congestion, crowd analysis, and emergent social behavior. This work provides a proof of concept for mobile sensor analytics that will help to improve network performance and provide safety personnel with information for better emergency planning and guidance.

Our paper is organized as follows: Section 2 discusses previous related work. Section 3 gives a brief description of the *eStadium* testbed. Section 4 discusses in detail, the visualization system we implemented along with the characteristics of the input data. Section 5 discusses how the visualization capabilities in our system aid in various analytic tasks. Section 6 presents some analysis and observations made by both visualization experts and system experts using our system for game data obtained in November 2005. Finally, section 7 discusses some possible extensions for mobile sensor analytics by combining data from various other types of sensors.

2 Related Work

Visual analytics research is a key focus at several research centers nationwide [10], and we build upon techniques developed at these centers in this paper. Most notably is the National Visualization and Analytics Center (NVAC) at Pacific Northwest National Lab (PNNL). Several projects developed at NVAC are related to our work. Their InfoStar system [20] has provided some inspiration for this project, while research by Wong et al. on large-scale graph visualization [24] and temporal analysis methods [23] has been ap-

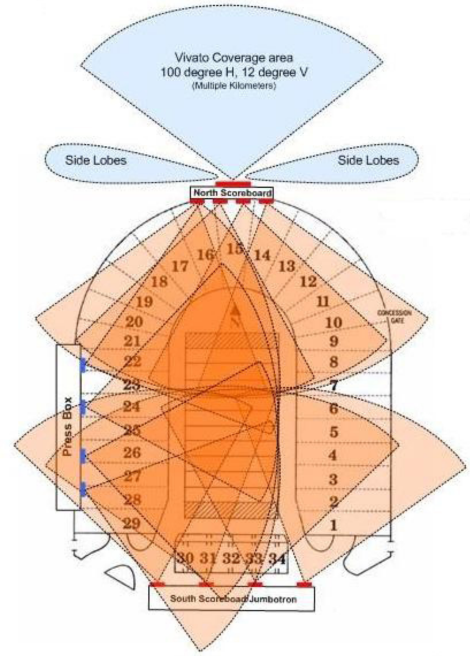


Figure 2: *eStadium* access point coverage. Presently access points on press box and south score board side are installed. Installation of access points on the north score board is in progress.

plied in the context of mobile visual analytics in this project.

The majority of visual analytics applications for mobile devices comes in the form of either mapping tools [13], sometimes enhanced with GPS capabilities, or convenience utilities [5, 14]. There have been efforts to use mobile devices in emergency response situations (such as the Measured Response project headed by the Purdue Synthetic Environment for Analysis and Simulation (SEAS) [1]), and for location-aware services. However, using a PDA for visual situational analysis is a fairly new research topic.

Of the visualization techniques employed in this paper, time-varying (temporal) graph visualization plays an important role. Time varying graph visualization is a common technique for network and relational analysis, for communication network analysis [11, 15], social network analysis [6, 22, 16], and relational [19] and geospatial data [12] visualization. With respect to communication networks, temporal visualization techniques are useful in detecting traffic anomalies and network intrusion events. In the social network context, time-varying visualization is used to display interpersonal communication activities between individuals, and these techniques lend themselves readily to the analysis of social trends, or knowledge propagation between agents. In both areas, visualizing task-specific events and relationships strengthens existing analytical techniques; however, none of these techniques are targeted for mobile information analytics.

Visualization techniques have previously been used in the context of sporting events to analyze human performance [9, 8] or for selective content delivery [18, 17]. Television broadcasting companies, such as CBS, employ systems such as VizEngine by Vizrt [2] in viewing sporting events in real-time, but these systems are generally for creating customized viewer content, not for detailed analysis of the respective events.

3 The *eStadium* Testbed

eStadium is a long-term, large-scale, collaborative project involving the Center for Wireless Systems & Applications (CWSA), Information Technology at Purdue (ITaP), and Purdue Intercollegiate Athletics [3]. The goals of the project include:

- Making Purdue's Ross Ade Stadium the most technologically advanced in intercollegiate athletics;
- Creating a "Living Lab" for research and education in the design and use of wireless networks;
- Identifying and solving problems in the on-demand delivery over a wireless network of multi-media applications to football fans' PDAs, cell phones, or other portable devices.

eStadium is known as a "Living Lab" because its wireless APs and content/load-balancing servers in the stadium support real users - football fans on game days. Via their PDAs or Smartphones, the fans can access a wide variety of football-related infotainment applications that have been developed by the *eStadium* Vertically-Integrated Project (VIP) team [4, 7]. These applications include: game play-by-play (a list of plays that is updated after each play) up-to-the-moment game statistics, player and coach bios, and a search tool for food concessions, stadium facilities, and local hotels and restaurants.

The most challenging application currently supported by *eStadium* enables fans to view video clips of game highlights [25, 26]. This real-time video distribution system consists of a Location Discovery System (LODS) and an admission control module implemented as a custom plugin under Windows Media Service, which limits the video traffic per AP basis. The client logging plugin was enabled when setting up the *eStadium* streaming publishing point so that the client-perceived video streaming performance can be recorded. Both the LODS and admission control are running as Windows services on the video server. These services store the client networking activities in the syslog and video streaming details in the streaming video log and dump them into a SQL server database for later analysis of video streaming and networking performance.

Cisco APs can be configured to send syslog messages to a remote computer; in our case, they are sent to the video server. The logged events can be chosen appropriately to help understand the status and movement of wireless clients. An AP sends a time-stamped syslog message whenever a client associates, disassociates, reassociates, authenticates or deauthenticates. These terms/actions, which are used later in the paper, are defined as follows:

Associated: This event occurs, and a corresponding message is generated, when a wireless client associates itself with an AP. Once the association process is complete, the wireless client can send and receive data packets via that AP.

Disassociated: This event occurs, and a corresponding message is generated, when a wireless client disconnects itself from the wireless network and disassociates with the currently associated AP.

Reassociated: When a wireless client changes locations and detects another AP with a stronger signal, it may decide to drop its association with one AP and start an association with the new AP. These two steps are reported as one event, called a reassociation, and only one message is generated.

Authenticated: Before the wireless client can associate with an AP, it must authenticate itself with the network. Since ITaP does not require authentication in the eStadium network, we do not see messages related to these events.

Deauthenticated The AP sends a de-authentication message when a wireless client has not sent or received any messages for a certain period of time or when the AP decides that the wireless device has left its coverage area.

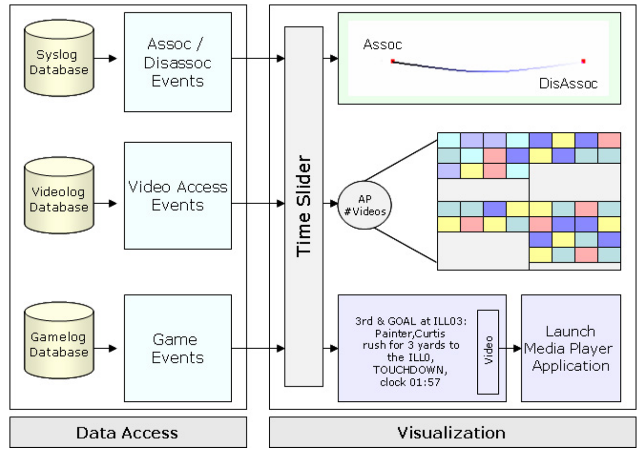


Figure 3: System overview

4 Network and Data Visualization on Mobile Devices

Mobile devices provide immediate and dynamic access to relevant real-time information in the field. For example, network analysts may need to make adjustments to load balancing factors, such as wireless AP power settings and preemptive broadcasting of certain types of data, as and when such issues present themselves on site.

With the *eStadium* testbed, we visualize network information and video and text information from games on mobile devices. Figure 3 shows our visualization system. As shown in the figure, we can access the database at selected time intervals and visualize the corresponding data synchronously. We present our data structures, layouts and primitives of our visualization according to data characteristics, and synchronization of all information in the following sections.

4.1 Data Characteristics

Data for our system comes from several sources, including data acquired from APs (hereafter referred to as "syslog" messages), video messages collected by streaming video servers (as mentioned in the section 3), and a manually-logged "play-by-play" of the sporting event in progress. Currently, all messages are parsed from historical data in the form of text logs, but the visualization system is designed to present both historical and real-time data. The parsed text logs of all types are stored on the PDA locally for instant access. Real-time data access will be provided during Fall 2006 games by direct access to the live SQL play database.

For our application, we consider syslog messages as a tuple consisting of a time-stamp, a message type (either "association" or "disassociation") and the MAC address of the client (connecting) device. Also, we consider any "Reassociation" message as an "Association" event for our application's purposes. The video messages have a similar format and contain additional information related to streaming video data, including which clip was requested, the number of requests, and other diagnostic information. Play-by-play or "game" messages consist of seven parts: the quarter in which the message is from, the game clock time within that quarter, a text description of the event, an optional video clip of the event, the type of play event (such as touchdown, interception, etc.), a label indicating which team holds the ball currently and the destination of the ball for the particular event.

In our implementation, we store the syslog and video messages in a hash table, hashed on device MAC addresses. We then generate a list of messages within a given time interval from this hash table. All events occurring in the same time interval can be queried/generated from the hash table using the same query. The lists generated by such a range query for each different type of multi-modal data can subsequently be traversed and translated to a relevant visualization.

Because we are working with multi-modal data on different time scales, we must organize our data carefully so our range queries will return events in the applicable time range. Our main issue is that while the syslog and video log data are recorded based on the real-world clock, the play-by-play data is currently logged based on the game clock. Therefore, it does not have a real-world time-stamp for each event. The closest association we have to remedy this situation is the first video access event for those game events for which a video clip is available. Such a remedy allows us to make an abstract association with real-time video events, but introduces some level of uncertainty with respect to when the game events occur.

4.2 Visualization on Mobile Devices

One of the main and obvious concerns for visualization on a PDA or smartphone is the lack of screen space. This becomes an even bigger challenge when we consider the limited computational resources on these devices. The main goal of visualization is to display information in a way that makes the user's cognitive task easier. While all visualization should display relevant data, the limited display resolution of mobile devices makes the appropriate visual representation even more crucial. We have to avoid cluttering the screen, but at the same time, we should also display all the essential information in an aesthetically pleasing manner. Hence we need to first extract relevant data at an appropriate level of abstraction, and then match the data to an appropriate visual representation. In the case of network data during a football game, we must also take into account the time variation, and provide synchronized visual display. The following sections describe how we solve these two problems in our system.

4.2.1 Information Selection

Our system handles several different data modes including syslog, video and text. In this case, filtered data not only must convey essential information on its own, but the various modes have to be correlated in order to convey meaningful information. Here we describe how we filter information for the individual data modes.

Syslog Data: The syslog data contains association and disassociation events of each PDA device in the stadium. For visualization purposes, we represent an "event" by a set of disassociation and association activities. For a given time interval, there are numerous such events. Displaying all these events would clutter the PDA screen and wouldn't add any useful information. So, we combine the events between a pair of APs in a particular direction and represent them with a single curve whose thickness is based on the number of such events. We also have to display the devices associated with each AP. This can be computed by tracking the AP with which a device has an association message without a corresponding disassociation message during a time interval.

Video Data: Video logs from the *eStadium* test bed contain information about how a client perceives videos during a game. Again, displaying all the minute statistics might not be of any practical use since it can crowd the screen. An analyst might be interested in looking at the request patterns of videos from various sections of the stadium. We visualize the number of video accesses from each AP for each different video.

Game Data: The *eStadium* group keeps track of play-by-play events with links to video replays for important events in the game. The information covered in the game data describes significant happenings during the game (for example, touchdowns or field goals). Events are logged by quarters, and events with particular significance are marked with a game-clock time-stamp. We display the text statistics and color code actions (touchdowns, field goals, etc.), from this game log and let a user play related video clips for events occurring in the current time interval.

4.2.2 Information Display

The visualization system consists of several views, each representing a different type of data. These are the initial view, network event view, video event view, hybrid view, video download statistics view, most popular videos list, play by play visualization, game event view and a color legend for different types of plays. These are linked views and are accessible from the initial view. By linking all these views to the timeslider interface, a user can switch between views for the currently selected time interval. Here we describe each of these views in detail and how they are linked to each other.

Main Screen: The main screen shown in Figure 4(a) shows the APs (represented as blue dots placed at their approximate physical locations relative to the stadium). Four of the APs (the rightmost column) represent the ones that are mounted outside the pavilion, and the row of four APs at the bottom of the screen are the ones inside the south score board. The remaining 12 APs are inside the stadium pavilion on the third, fourth, fifth and sixth floors. To differentiate these 12 APs, we draw a semi-transparent rectangle around them. The layout of these APs in the stadium can be seen in Figure 1. Two of the APs on the third and fifth floors aren't shown in this figure, because they aren't typically used. We have a time slider at the bottom of the screen which can be moved in either direction. It enables a user to scroll through continuous time intervals and see the visualization corresponding to the time interval between its current and previous positions. The time range for the slider is set to the minimum and maximum time-stamps from the log files. There are eight screen modes for displaying different information and all of them are synchronized with the time slider. The synchronization helps a user or an analyst have situational awareness with respect to various aspects of the game such as network access, video access and important events in the game at the same time. Buttons at the top of the screen help a user switch between the screen modes. These screen modes of our system are as follows:

Network Event Screen: This screen shown in Figure 4(b) displays sets of association/disassociation events of devices in the stadium. For each selected event per device (event selected as mentioned in the previous section) we draw a curve with random curvature from the source (AP to which the device was previously connected) to the destination (AP to which the device reconnected). The direction is indicated by the changing opacity, with the opacity value increasing from the source to the destination. Colors for the curves were chosen to distinguish them from other visualization aspects, and will be used for attribute visualization in the future. Events from the prior time interval are drawn as semitransparent to represent past events while also retaining the context. To reduce visual clutter, we draw curves with thickness proportional to the amount of activity in a particular direction between a set of APs Devices actively associated with an AP during a time interval are represented by transparent squares in a circular distribution around the corresponding AP.

Video Event Screen: The video event screen in Figure 4(c) shows how many videos have been accessed from each AP. At each AP location, circles are drawn with size based on the quantity of videos accessed. A user can then examine an exploded view (in the subscreen labeled as "Video Event Subscreen" in Figure 4(c) on the left) of individual video accesses. It is divided into four portions (one for each quarter, starting from the top), with each portion representing videos uploaded for a particular quarter. The quadrant corresponding to the current game quarter is highlighted as the user moves across time periods. For example, we can see the highlighted second quadrant in Figure 4(c). Each interior square indicates a unique video associated with that particular quarter. The opacity value of each square is proportional to the number of down-

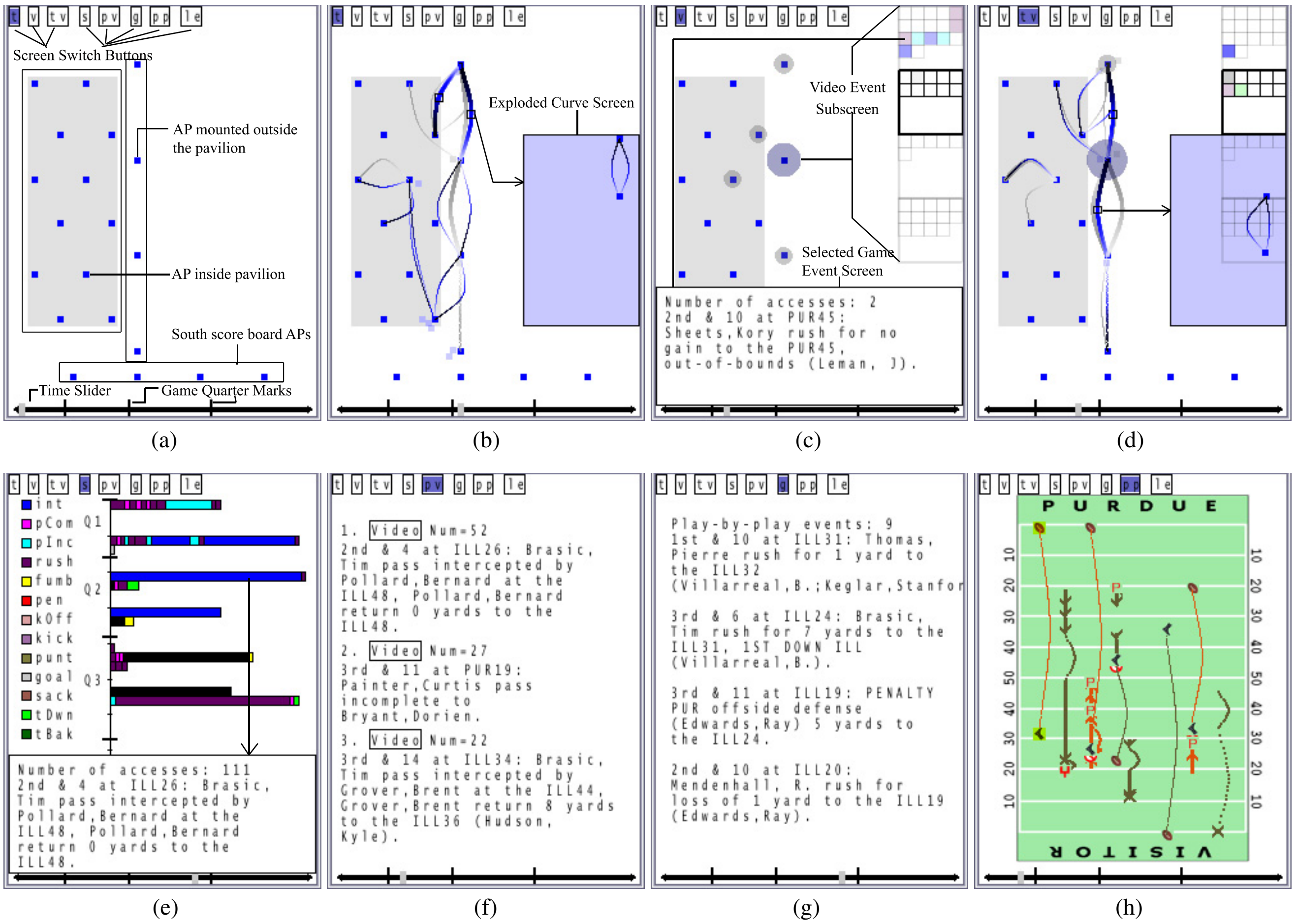


Figure 4: Different screen modes of our visualization showing **(a) Main Screen:** Main screen with APs, time slider and screen buttons. The row of four APs at the bottom are the south score board APs, the rightmost column represents the APs mounted outside the pavilion and the remaining are the ones mounted inside the pavilion. **(b) Network Event Screen:** Association/Disassociation events of the current (blue) and previous time interval (grey). If there are multiple movements in the same direction between two APs, its exploded view is shown in a blue screen inset into the main screen. **(c) Video Event Screen:** Video Access per AP and Individual video access details. Inset, is the text describing the event corresponding to a selected video from the Video Event SubScreen. **(d) Hybrid Screen:** Hybrid mode showing both (b) and (c). **(e) Video Statistics Screen:** Video download statistics in the form of a stacked bar graph, and text description corresponding to a selected video from the graph. Color legend is displayed on the left, with abbreviated names for each play type. **(f) Popular Video Screen:** Three most popular videos from the current time interval, along with their number of accesses are displayed. Video link plays the associated video and the text description corresponding to the game event is displayed below the video link. **(g) Game Text Screen:** Game play-by-play events as text. **(h) Play by Play Visualization Screen:** Visualization of play-by-play events in the current time interval, shown as drives for each team.

loads of that particular video. The highest opacity is mapped to the video with the most downloads. The square color is based on the class of game event to which the corresponding video is related. The classes include touchdowns, interceptions, rushes, and passes, to name a few. This will help an analyst effortlessly correlate video download patterns to the type of game event.

Hybrid Network and Video Event Screen: This screen displays the combined information from both the views mentioned above and can be seen in Figure 4(d)

Video Statistics Screen: In this screen (shown in Figure 4(e)), we display the statistics of video downloads incrementally for each time interval (as the user steps through the time axis), as a stacked bar graph. The graph is drawn vertically for lack of screen space. The graph axis is marked with two types of tick marks. Smaller ticks on the axis represent individual time intervals and the larger ticks represent game quarter marks. On this graph, in a given time interval, there is space for four bars, one for each quarter. Each bar by itself consists of multiple stacked rectangles one over the other, with their individual sizes representing the number of videos downloaded in that time interval and color coded based on the type of game event. Clicking on any of these rectangles will display the number of accesses to the video and the corresponding game event as text within a small window. We also display a color legend, for the colors used in the bar graph. The play type corresponding to each color is displayed as text in abbreviated form.

Popular Video Screen: This screen (as shown in Figure 4(f)) displays the list of top three videos downloaded by fans in the current time interval. For each video, it displays a "video" link which plays it in Windows Media Player. The number of downloads of the video is displayed beside the video link. The text description of the corresponding game event appears below the video link.

Game Text Screen: This is a text display showing the important events in the game logged by the *eStadium* team in the selected time interval. This view can be seen in Figure 4(g). It shows a subset of events from the current time interval.

Play by Play Visualization Screen: This is a functionality that we added to improve fans' game experience. As shown in Figure 4(h), it displays important play by play events in the game using various visualization entities. Each play is displayed based on the type of action such as interception, field goal, pass, etc. A "Rush" action is displayed using an arrow in the direction of the rush. "Pass", "Kick" and "Punt" actions are displayed using curves and appropriate icons for each event. Similarly, we have icons to represent events like "Penalty", "Incomplete Pass", etc. where the ball isn't moved by the player. We represent the play events in the current time interval as continuous drives starting from the left moving to the right for each drive. A user can click on any of the icons or arrows to view the selected game event screen displaying the text description of the corresponding play.

Exploded Network Event Screen: This is a subscreen inset into the main screen. As mentioned before, each network association/disassociation event is drawn as a single curve with thickness proportional to the amount of activity. So, each curve with number of events greater than one, is drawn with a small square on it. A user can click this square to view the detailed view. This screen shows the exploded view on the right side of the screen as can be seen in Figure 4(b). Within this screen, the specific APs are drawn maintaining their relative orientation and position with respect to each other so that it is easy for the user to correlate between this screen and the main screen. The screen can be closed by clicking on the top right corner.

Selected Game Event Screen: A user can see the game event corresponding to a video by clicking on such an item and pop up a screen at the bottom of the screen (just above the time slider) as can be seen in Figure 4(c) and (e).

5 Visual Analytics Issues

Visual analytics typically deals with multi-modal data which require specific visualization techniques for each modality. This section explains some of these issues and their solutions in our visualization system.

Temporal Visualization: Data for visual analytics is usually time varying. Specifically, in our case, network data is collected over the entire duration of the football game, and can be streamed during the game. Our system includes a time slider, which allows a user to move back and forth in time and view the visualization related to that time interval. All modes of data (syslog, video and text data) are synchronized with the time slider. In order not to lose continuity between subsequent time intervals, we also "ghost" the events from the previous time interval in a faded color.

Additionally, as stated earlier, time synchronization and correlation issues must be considered with multi-modal datasets. With respect to this work, only two of the three data sources have global clock information, while the other dataset only has time-stamps relative to the game clock. Subsequently, efforts must be made to link these events to the datasets ordered in global time. This introduces some measure of uncertainty, which we must be aware of in the analytical process.

Information Clustering: As mentioned before, a big challenge for mobile visual analytics is the limited screen space. To overcome this limitation, information has to be visualized selectively and related information has to be grouped together. A user should be able to then view details at multiple resolutions when desired (detail on demand). In our system, we employ information filtering as mentioned in 4.2.1. Multiple events between a set of APs in a particular direction are grouped together using a single curve with proportional thickness. A user can then see its exploded or detailed view in the Exploded Network Event screen (shown in Figure 4(b)). Similarly, all video access events per AP are shown as a single circle. A user can then view the detailed video access information for any selected AP. A user can view even more detailed information about the game event corresponding to any particular video in the Selected Game Event Screen (shown in Figure 4(c) and (e)).

Multi-modal Data Visualization: Analysts usually have to work with data from multiple sources in various formats and correlate them. Using our system, the user can visualize syslog, video and text data linked with each other while keeping the context of the current time interval constant. Since all these modes of data are interlinked, a user can switch between any of these from any screen.

Analytic Tasks: The *eStadium* team plans to use our prototype system during Fall 2006 football games for various analytic tasks. One of the main issues at hand is with respect to load balancing. Our system will be used to identify network bottlenecks for the APs, as well as for streaming video. The usage patterns of association and disassociation can help coverage/capacity planning, QoS provisioning and support location-based services. Power level settings of the APs will also be adjusted based on these in-field observations. The power level settings for the APs in the stadium are important parameters that should be tuned to maximize the available channel capacity. When many APs are operating in the same area, there is a tradeoff between coverage and interference. Determining the power settings that yield the best combination of coverage and quality of service is a significant challenge. Moreover, though network load balancing is adjusted automatically, an analyst needs to be able to determine if the load balancing algorithm is performing correctly on site.

Also, from the video log visualization, one can immediately estimate the source location for the video requests and also the type of events for these videos based on the color coding (touchdown, interception, etc.). Recognizing such patterns can help the network administrators decide to preemptively broadcast or multicast to these locations when certain events happen. The popular video display also helps a game fan go back and effortlessly look at the most popular video replays in case he missed a part of the game.

6 Implementation and Results

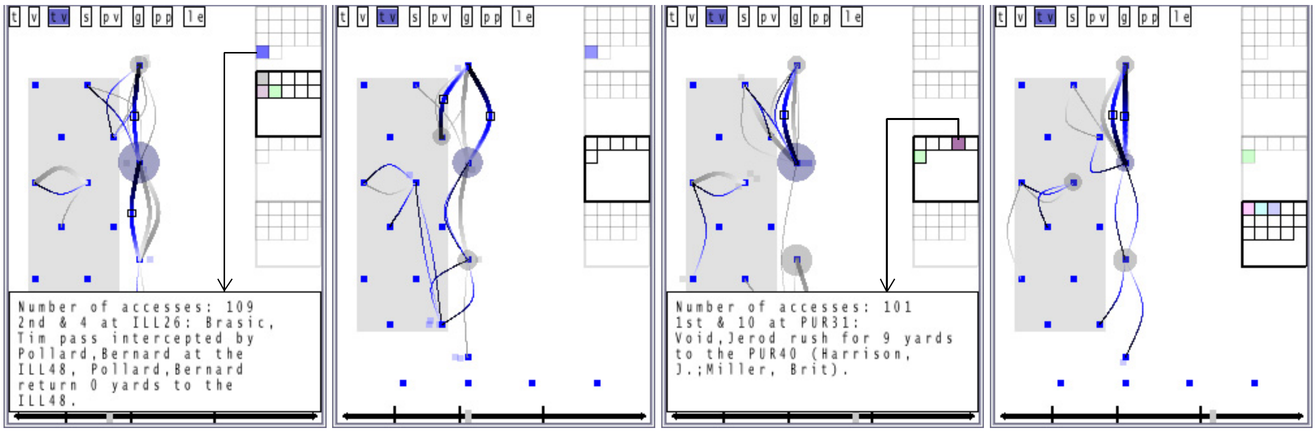
We have implemented and tested the system on a Dell Axim x51v PDA with a screen resolution of 240 x 320, but it will run on any PDA or a smartphone with sufficient graphics and processing capabilities. Photos of our system running on a PDA are shown in Figure 6. We use the OpenGL ES API for development. It is a low-level, lightweight API for advanced embedded graphics and is a subset of the traditional desktop version of OpenGL API. A significant change in OpenGL ES is that all the drawing calls are done using vertex arrays and color arrays, since glBegin() and glEnd() calls are absent. We also use GLES common lite profile which uses fixed arithmetic instead of floating point computation, since floating point arithmetic is emulated on the PDA.

The data for visualization is obtained from the *eStadium*, LODS and streaming video databases. Currently, we do not have real time data since it is off season for football. We query the previously mentioned database to obtain historical data from last year's Purdue-Illinois game on November 12, 2005.

The graphics environment is set up as a 2D orthographic projection since the visualization entities are all 2D. All of the buttons used to switch between various screen modes are drawn using graphics calls and the text is rendered using texture-mapped bitmap fonts. Stylus input is handled by the mouse function of the GLUTES library. Video playback functionality is handled simply with a call to the external Windows media player.

Using the visualization, we are able to do a simultaneous observation of which were the APs with heavy video requests (from the video event screen), which individual videos among them had the highest hits (detailed video event sub screen), number of hits and what was the related game event (from the Selected Game Event screen).

The results from our system can be seen in Figure 4 for different timesteps and visualization screen modes. Based on an overall analysis for this game data, we observe that there are many association/disassociation events, as well as video downloads from the four



(a) (b) (c) (d)

Figure 5: Visualization at different time intervals for the 11/12/2005 Purdue-Illinois game. All of these show a high activity around the four APs outside the pavilion and the third floor APs. (a) also displays the text description of the play-by-play event corresponding to the video shown as a dark blue square. This interception video has been the most often downloaded video during this game. (b) shows that even though the time slider is in third quarter, at that time, people are downloading video from the first quarter (shown as blue square). (c) shows another popular downloaded video shown as dark purple square with its text description. (d) also shows how people are still downloading popular videos from previous quarters.

APs outside the pavilion and none to or from the four APs near the south score board (Figure 5(a), (b), (c) and (d)). The circle around the AP which is currently selected to view the detailed video access screen is highlighted in blue to differentiate it from the others. In Figure 5(b) and (d), we can also observe that fans typically tend to access important play videos from previous quarters as the game progresses.

Based on a more specific analysis, we observe the following behavior:

The Network Event Screen (Figure 4(b)) shows that most switching between APs seems to be "tit-for-tat" in that it is likely the same mobile device is associating back and forth between APs. This is generally caused by a poorly designed driver on the client device, indicating that we need to perform some further analysis to determine if the jumping is occuring from our set of PDA's or from outside user devices.

The Video Event Screen (Figure 4(c)) shows that the vast majority of video accesses are coming from the northern, third-floor region of the pavilion. This is an indication that the power level settings of the APs should be reduced in that area while at the same time restricting the client association rates in order to serve more clients with the desired quality of service.

The Hybrid Network and Video Event screen (Figure 4(d)) shows that most of the AP hopping is occurring in the regions of the network where the highest number of video downloads are occurring. It is unclear at this point how much of this phenomena is related directly to the amount of traffic at an AP, and how much is caused by the tautological fact that usually the only APs with devices connected are the ones that are downloading video.

Also, the visual analytics of the syslog data made it clear that simply matching each association with a disassociation is inadequate to estimate session count and length. This is because the associations and disassociations are out of order and not quantifiably matched. This spurred research into the cause of these errors:

- the syslog messages are sent using UDP, meaning that messages will arrive at the syslog out-of-order, and some could be lost

- reassociations after a timeout period seem to cause the majority of the discrepancies between the number of associations and disassociations

We are currently investigating a more complex method of analysis to better understand the syslog events.

The Video Statistics Screen (Figure 4(e)) makes it clear that the vast majority of video download requests are for a very small subset of videos (in this case, interceptions and touchdowns), although the time of the request is not always predictable. This indicates that multi-casting these heavily-accessed videos should significantly increase the number of clients we are able to serve simultaneously.

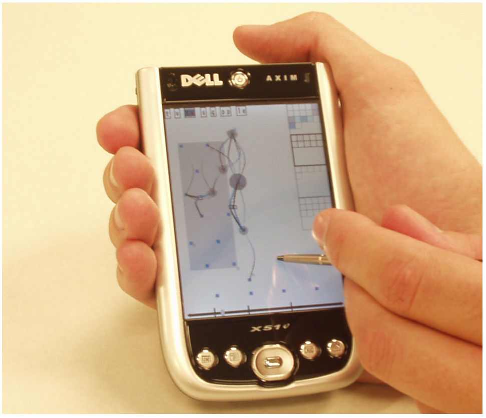
7 Conclusion and Future Work

We have shown in this paper how we can develop an interactive visualization system for analysis of network data. Our system displays time-varying multi-modal data in a synchronized fashion. It helps an analyst process data simultaneously without losing context while switching between visualization of different modes of data. Moreover, since it's developed for a mobile device, a user can use it in real time on a football stadium or anywhere else in field for immediate analysis and respond if necessary.

For example, we discovered that some APs were totally free of any association/disassociation, while during certain time intervals there was marked activity between a particular set of APs. Observations such as these will be of use to our network analysts in determining usage patterns and parameter settings of APs.

User and network statistics are generally very useful in network troubleshooting. Plans to integrate specific network characteristics, such as link quality/packet loss, users per AP details, and throughput information, are in progress. Also, additional exploratory abilities within our current visualization of AP data would be of service in determining link outages and identifying wireless access patterns.

As future work, the integration of temperature, acoustic, and video sensor data in the Fall 2006 will allow us to detect several characteristics that are currently unavailable. Using such data, we can provide estimates on where crowds tend to populate in the stadium and provide location-specific services based on crowd density. Also the integration of emergency response data based on sensor information will be added. By using crowd density measurements, we could provide crowd guidance information to emergency response personnel, such as optimal exit paths. Moreover, we can extend our system to identify fire hot spots using temperature sensors within



(a)

(b)

Figure 6: Photos of our system running on PDA

the stadium and prepare fire-fighters appropriately based on that data.

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