Workflow and Application Adaptations in Mobile Environments

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Abstract

This position paper describes applications that can benefit from integrated mobile computing and workflow management technologies. Such applications empower a mobile workforce to perform coordinated and streamlined work activities in the field or on the road. We discuss characteristics of these applications and workflow management for supporting these applications. We suggest that mobility support not only extends the application domains of workflow management, but also raises more general issues concerning adaptation paradigms for supporting mobile applications.

1. Introduction

In a large number of organizations, the daily operation is governed by a set of cooperative business processes in which intensive group-oriented human interactions are involved. A business process is an ordered (or coordinated) set of work activities. Workflow management provides the ability to improve the efficiency of an organization by streamlining and automating coordinated work activities over distributed environments.

Currently, most workflow management systems support workflow participants (or users) for performing work activities only in office environments. The growing popularity and maturity of mobile computing, however, have rapidly made it reality that many work activities can be computerized and automated outside the office. There are two implications to the automation of business processes using the emerging mobile computing technology. First, work activities that used to be performed within the office now can be done remotely, independently of a worker's location. Second, on-site work activities that had to be performed manually in the past can be computerized and automated with the advent of mobile computing. In this sense, mobile technology and solutions not only increase flexibility for existing systems and applications, but also provide broader benefits for organizations through the redesign of business processes. To facilitate such improvement and redesign, it is compelling to provide support for a mobile workforce in workflow management systems.

In this position paper, we present our on going research work on mobile workflow management at GTE Laboratories. This research focuses on extending workflow technology to support a mobile workforce for performing work activities in business processes. We first describe characteristics of applications that could benefit from mobile computing and workflow management technologies. Then, we discuss adaptation issues in workflow management for supporting these mobile applications. In particular, we identify workflow-specific adaptation and application-specific adaptation as two complementary capabilities that provide improved mobile solutions for workflow applications. To demonstrate the capabilities, we describe adaptive strategies that deal with the dynamics of mobile resources in workflow resource management and the constraints of bandwidth in electronic document processing.

2. Workflow Applications in Mobile Environments

In the first part of this section we present general terminology about workflow management systems and applications. In the second part of this section we present two examples of mobile workflow applications.

2.1. Workflow Management and Applications

A workflow management system supports the definition and execution of workflow processes that model business applications through a coordinated set of process activities (or work activities). A process activity may be a manual activity or an automated activity. A manual activity can be represented as a work item in a worklist pending completion by a workflow participant (or user). The workflow management system is also responsible for the specification of workflow resources in the definition of workflow processes and the binding of workflow resources to work activities at run time. A workflow resource can be a software, hardware, and/or human resource that performs a work activity (see Figure 1).

Examples of applications that can be modeled by workflow processes are insurance claim processes and purchase approval processes. We call an application that can be modeled and executed through workflow processes a *workflow based application* or simply a workflow application. From the implementation perspective, workflow applications are distinguished from conventional applications in that activity sequencing and coordination and organizational structures and resources are separated from application programs (or code) in workflow applications and managed by workflow management systems. In conventional applications, in contrast, the information about the process logic and resources is hard-coded into application programs. The separation makes workflow applications flexible and easy to maintain because a change in business process or organizational structure does not always require a change in the application program itself. The separation of organizational structures and resources from code also optimizes the utilization of resources and improves the efficiency and responsiveness of workflow applications.

Applications that are invoked for the purpose of initiating and executing work activities are called *workflow invoked applications* or invoked applications. For example, a work item assigned to a workflow user (i.e., a human resource) requires editing a Word document. In this case, the Word program is a workflow invoked application that is invoked for Word document processing. In this paper, the term of workflow applications is used for workflow based applications, not for workflow invoked applications.

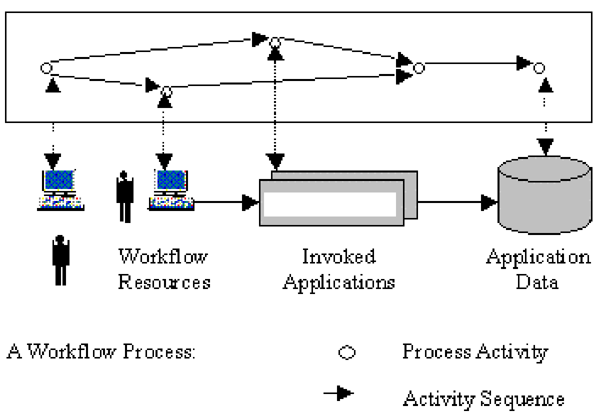

Figure 1. Workflow Processes and Applications

2.2. Mobile Workflow Applications

For many companies, the attraction of mobile computing is based on the fact that large productivity gains are possible in the out-of-office workplace. Among the current users of mobile solutions are healthcare, utilities, surveying, transportation, telecommunications, and emergency response organizations. Mobile solutions offer productivity gains by streamlining and improving existing functions or by introducing new applications that are possible only with the advent of mobile computing.

To fulfill these productivity gains, it is compelling to provide mobility support in workflow management. This mobility support allows mobile resources (e.g., a mobile worker carrying a mobile device) to perform work activities in workflow applications. We refer to workflow applications that involve the use of mobile resources as *mobile workflow applications*. Mobility support releases workflow users from "location" constraints in performing the work activities that used to be done only in the office environments and also enables the computerization and automation of on-site work activities that had to be performed manually in the past. The work activities in the former case are referred as location-independent activities, while those in the latter case are referred as location-dependent activities.

To better understand the requirements for mobility support, we describe two application examples that can benefit from mobile computing and workflow management technologies and identify the characteristics of each.

Example 1. On-Call Field Services: Many activities carried on in the out-of-office workplace are inherently spatial in nature, i.e., they are location-dependent. On-call field services, for example, involve physical maintenance and service activities at customer sites.

The primary goals for automating on-call field service processes include reducing the lag-time in the customer billing cycle, tightening inventory control for equipment parts, downsizing central dispatch personnel, and replacing paper documents such as customer documents, service records, and part order and receipt forms by electronic documents.

To support the automation of on-call field service processes, on-call representatives are outfitted with laptops and cellular telephones. They are able to communicate via a cellular phone while on the road or at a customer's site and from direct dial-up at their home. Representatives are also equipped with portable printers for generating service records and other documents for their customers in the field.

When customers call the central dispatch facility, pertinent information is logged into databases. The appropriate on-call representative will be assigned to the call based on the representative's availability, qualifications, and proximity to the customer service site. Once assigned, the on-call representative is paged via a standard pager. If the on-call representative is driving, s/he simply pulls over and dials via cellular phone into the corporate database server. Once logged into the server, the laptop automatically downloads information needed to perform the assigned task, including the ticket describing the location and nature of the service call, parts requirements, and graphical documents such as hand-sketched maps, schematics, and equipment disassembly instructions.

The on-call representative replies to the assignment with an estimated time of arrival at the customer site, logs his/her time, requests required parts, checks the status of parts being sent for other service calls, and updates the dispatch database of his present location. When the on-call representative returns home at night, s/he connects the laptop to his/her telephone line to operate under “nighttime” mode. The laptop is set up to automatically dial into the database server at a scheduled time to receive parts inventory updates from the parts depot and software updates etc. The inventory update shows which parts are on order, what failed equipment parts have yet to be sent back, and which parts were shipped from the depot for the following day’s work.

This example shows how mobile computing supports mobile workers to perform coordinated work activities. It demonstrates the following characteristics of this process:

1. The activities to be performed by mobile workers could be location dependent. For instance, an activity could be on-site equipment maintenance.

2. The resources needed to perform these activities are moving constantly. For example, on-site equipment maintenance requires an on-call representative (i.e., a mobile worker resource) carrying equipment parts (i.e. a part resource) in the back of van.

3. The time needed to complete an assigned task is a function of resource location. To minimize the time (including the driving time), an on-call representative who is nearby should be assigned.

Similar process examples that involve coordinated location-dependent and on-site activities include parcel delivery services, transportation systems, taxi services in the civilian industry, and digital battlefield in the military. With mobility support added to workflow management systems, these processes can be defined and automated by the application of mobile resources for work activities. This support will facilitate the seamless integration of mobile resources and application tools such GIS, GPS, and dispatch package etc. For instance, in the field service application, the dispatch software package could be tightly integrated in a workflow process to provide dispatch output for the assignment of mobile resources.

Example 2. Insurance Service Process: In an insurance service application, customer service managers often perform work activities such as signing RFP forms and processing customer complaints in the field or on the road. Each activity needs to process a collection of electronic documents generated from scanned paper forms, letters, or color photos. For example, the customer service manager is assigned a series of work items that review and process customer accident claims. Each work item includes a collection of electronic documents covering one accident claim case (see Figure 2). Among these documents are four image files (in TIFF format) generated from a scanned customer claim, the customer insurance policy, color photos, a police report, and two Word files for reply letters to the customer.

Figure 2. Electronic Documents Attached in a Work Item

The application in the above example has the following characteristics:

1. Electronic documents attached to each work item can be large in size. For example, a compressed image with 24 bit-TIFF format could be about 200-400K for a 4"x6" color photo. A black and white TIFF image for a letter is typically about 50K (after it is compressed). The total size for the attached documents could be as large as 720K (assuming two Word text files - 2 X 10K, two color photo TIFF files - 2 X 300K, and two black and white TIFF files - 2 X 50K);

2. Mobile users may process electronic documents from different places with various network connections, wireless or wired. In the low bandwidth wireless connection, data transmission can be time consuming. For example, with a 56Kb wireless link, it would take about 2 minutes to transfer the documents above.

With the mobility support in workflow management, the mobile users could process a series of these customer claim cases continuously without incurring a long waiting time for the transmission of documents over low and varying bandwidth links.

3. Workflow-Specific and Application-Specific Adaptations

To effectively support mobile workers for performing process activities (both location-dependent and location-independent), many issues should be addressed and understood from both the mobile computing and workflow management perspectives. How should mobile resources and activities be modeled and expressed in workflow processes? Which workflow management functions should be responsible for enabling mobile users to perform work activities? What type of adaptation of workflow management systems and applications could be applied to deal with the uncertainty and dynamics of mobile environments?

The rest of this paper focuses on techniques for adapting workflow management systems and applications to the mobile environment. We identify two adaptation paradigms that support mobile workflow applications: workflow-specific adaptation and application-specific adaptation. We describe adaptive strategies for mobile resource management and electronic document processing. These strategies demonstrate the complementary capabilities of the two paradigms in providing improved mobile solutions for workflow applications.

Workflow-specific adaptation is characterized as a strategy that is conducted by workflow functions (e.g., workflow enactment services or worklist handler) or their extensions. Application-specific adaptation is a strategy that is achieved by workflow invoked applications, application-specific utilities, or their extensions (see Figure 3).

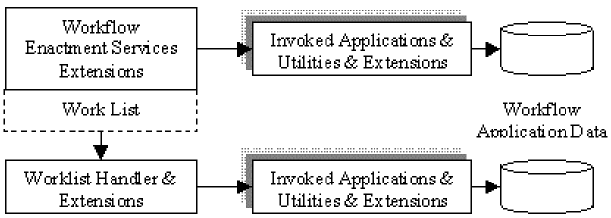

Figure 3. Workflow and Application Adaptations

3.1. Mobile Resource Management

Resource management in workflow management systems is concerned with efficient tracking of resource status and the assignment of resources to work activities at the execution time of processes. Resource management is relatively easy if all workflow resources are always connected and not subject to frequent change. The problem becomes difficult when resources are frequently moving and disconnected (or weakly connected) as in many mobile environments. If a mobile resource is to be assigned to a location-dependent activity, the problem becomes even harder. This is because it is difficult or expensive to maintain synchronization between the resource databases in workflow management systems and the actual resource status due to the dynamics and disconnection of mobile resources.

One way to ease the synchronization problem is to use a bound on the deviation between the actual value and the database value (i.e., the value stored in the resource databases) for each resource. For example, the mobile resource will send a location update to a workflow management system only when its deviation exceeds the bound. In this way, the mobile resource does not need to connect to the workflow management system all the time and the workflow management system estimates the location of mobile resource with an error (i.e., deviation) specified by the interval bound.

Although the deviation control can ease the synchronization problem, the deviation may still not be controlled within the designated bound all the time because of the overhead of synchronization and the disconnection of mobile resources. As a result, load estimation and assignment decision could be made inaccurately. To deal with the dynamics and unpredictability of mobile resources, we propose adaptive strategies for resource assignment and work item prioritization.

Hybrid assignment strategy: This is an example of workflow-specific adaptation. The workflow resource manager adapts to changing resource status by applying an appropriate assignment policy to each type of resource. A resource can be assigned to a work item either at the time when the work item is enabled for assignment in a workflow process instance or at the time when the resource is connected and ready to select work items for execution. The former assignment is an optimistic policy because it is performed before the resource is connected and becomes available for use, while the latter assignment is a pessimistic policy because it defers the assignment until the resource is connected and ready to select work items for execution.

The optimistic policy is simple and works well for resources whose status is predictable and infrequently changed. This policy is used in most current workflow management systems. However, it might not be suitable for the resources that are dynamically changed or frequently disconnected. In fact, the uncontrolled deviation of resource due to disconnection could invalidate an early assignment decision. The inaccurate decision may leave a work item assigned to the wrong resource for an indefinite period of time, which degrades the utilization of resources and the responsiveness of applications. The late assignment in the pessimistic policy, on the other hand, can relieve this inaccurate decision problem. However, the scalability issue has to be addressed, since a late assignment may incur a visible latency to the workflow participant who is to select work items. The latency cannot be overlooked when the number of work items and the number of resources managed by the workflow system are very large. The latency could increase if time is needed to compress or format workflow application data (e.g., image documents) before assigned work items and attached workflow application data are transferred to the mobile device.

To address the dynamics of mobile resources and the efficiency of assignment, we advocate an adaptive hybrid assignment strategy that applies the optimistic policy for predictable and less frequently changed resources and the pessimistic policy for frequently changed and uncontrolled resources. The key to the hybrid assignment strategy is to differentiate the resource types based on the controllability of deviation and apply an appropriate policy to each of them. A resource can be treated as a controlled resource if its status has been within the deviation bound for the last 'm' (a threshold value) connections. Otherwise, it is classified as an uncontrolled resource. An uncontrolled resource is assigned to work items only when it connects to the resource manager. Note that these work items may have been assigned to other resources, but not yet been selected. A hybrid assignment reduces to the pessimistic policy when all resources are treated as uncontrolled resources and to the optimistic policy when all resources are treated as controlled resources.

An alternative to the late assignment for uncontrolled resources is to use deviation correction in which all resources are considered as controlled resources and assigned to work items based on the information in resource databases. A deviation correction is trigged whenever an uncontrolled deviation is detected for a resource. The resource manager evaluates the work items assigned to the resource and assigns other work items to it if possible. But, there is an overhead for the deviation correction, which includes the time needed to evaluate the load of resources and assign new work items.

Item prioritization strategy: Another way to address the dynamics of mobile resources is to use a strategy of application-specific adaptation for the prioritization of work items. Work items assigned to a workflow participant are presented through a worklist window. The prioritization functions change the work item ordering in the worklist based on the information specific to invoked applications and application data or the knowledge about the changes of resource status from the mobile user. The prioritized ordering facilitates the workflow participant in selecting assigned work items.

The prioritization capability is attractive for two reasons. First, as we discussed before, work items may have been assigned inaccurately due to disconnection or status changes. Item prioritization could be used to prevent the workflow participant from selecting these work items before the resource manager corrects the inaccurate assignment. The prioritization could also be used to deal with the dynamics of mobile resources in another way. That is, the knowledge about the future status of a resource from the mobile user (e.g., the moving direction or the new location of mobile resource) can be used to prioritize the work items in the worklist.

Second, a mobile workflow participant may have replicated part of databases on the laptop as workflow application data before work items are selected and checked out. In this case, the prioritization capability lets the participant know which work items can be selected and performed with the least latency of transmission of application data over low bandwidth connections.

The prioritization decision can be made based on the metrics such as the communication cost and latency, or the time needed for work item processing and the parameters such as the network connectivity, the quality level of data and the application-specific information like customer names and locations etc.

Complementary and collaborative capabilities: The above two strategies demonstrate the complementary capabilities of workflow-specific adaptation and application-specific adaptation. The hybrid assignment strategy applies different assignment policies dynamically based on resource types to deal with the dynamics of resources. In contrast, the item prioritization strategy applies the application semantics and the user knowledge about the changes of resource status to prioritize assigned work items. The hybrid assignment allows a global level optimization because the assignment takes into account all resources and activities managed in workflow management systems. The item prioritization is a local level optimization because it considers only the work items that have been assigned to the particular workflow participant (i.e., a human resource).

The collaborative capabilities between two strategies could also be explored. For example, the hybrid assignment strategy could react to the decision of prioritization selection by reassigning the work items that are not selected to or from other resources. This collaboration, therefore, provides a way for workflow resource management indirectly to react to changing environments based on information or semantics specific to applications or user preferences.

3.2. Electronic Document Processing

A common activity in workflow applications requires processing electronic documents (e.g., for signing approval forms, processing customer complaints, or editing service letters, etc). An electronic document consists of a collection of image and text data. Examples include image documents, Word documents, or web pages. An image document could be a collection of faxes, memos, and photographs that are scanned to a multi-page image file. Image data in electronic documents can be very large in size in terms of the number of digital bits they represent. We propose adaptive strategies that provide seamless and flexible workflow-based document access over varying and low bandwidth links. The proposed strategies offer optimization and flexibility when document data cannot be transferred fast enough without lowering data quality.

Background pre-fetching strategy: This is a strategy of workflow-specific adaptation that is initiated and controlled by workflow functions (e.g., a worklist handler). The idea is to pre-fetch (or migrate) document data for each assigned work item into the user's mobile device and rebind the fetched data to the work item before it is processed. Once a work item is bound to the pre-fetched data, the work item is automatically selected for the user and removed from other users who have been eligible to work on the item. The pre-fetching process is performed concurrently (in the background) while the user is processing another item. If the pre-fetching time (i.e., the transmission time of document data) is less than the processing time for assigned work items, the latency for data transmission could be invisible to the user.

The adaptation is supported in two different ways. First, the procedure dynamically decides the order of work items that are to be fetched based on the user's speed of document processing, the available network bandwidth, and the size of document data for each item. For example, when the available bandwidth is low, the work items with the small size of document data are pre-fetched. If more bandwidth is available or the user's speed for document processing gets slow, the work items with the large size of document data are pre-fetched.

Second, the pre-fetching can transfer compressed images at a lower quality level to match user's speed of document processing over low bandwidth. The compression depends on pre-determined parameters such as the acceptable quality level (i.e., the lower bound of quality level) and the acceptable transmission rate for work items (i.e., the lower bound of transmission rate).

On-line fetching strategy: Over low-bandwidth connections, background pre-fetching may not match the user's speed of document processing without lowering the quality of document data (e.g., images). For this case, instead of reducing the quality of (image) data in background, the users can be given options to decide at what quality level these data can be fetched at the on-line time when the document for the work item is opened and being transmitted for processing. This is a case of application-specific adaptation.

The user can change the quality of image data for a desired performance at the time of document processing. The user can also either stop the on-line fetching immediately or wait longer for a better quality image. If the pre-fetching functions place low quality of data copies in a client cache, the on-line fetching allows the user to get refined copies. Since the on-line fetching strategy lets the user control the quality of images at document processing time, it offers more flexibility and optimization for the bandwidth utilization than the pre-fetching strategy does.

Complementary and collaborative capabilities: The on-line strategy could offer an optimized use of bandwidth for those data (e.g., images) that allow a tradeoff between quality and performance, while the pre-fetching strategy is useful for document data (e.g., text data) that cannot benefit from such a tradeoff. These two strategies offer complementary capabilities for document processing. However, on-line fetching incurs an observable latency for the on-line transmission of data. The adaptation capability (e.g., ordering work items to be fetched) of pre-fetching could be limited when the bandwidth becomes too low. The pre-fetching strategy may not maximize the effective utilization of bandwidth, since it cannot take advantage of application semantics for data compression.

For document processing, it is desirable for the two strategies to collaborate with each other to maximize the benefits of each strategy. The collaboration decides how the available bandwidth is allocated for each type of strategy, what type of data in each document should be fetched by each strategy, and at what quality level these data can be fetched. This collaboration is desirable when the bandwidth is low and the background pre-fetching cannot match the user's speed of document processing without lowering the quality of document data (e.g., images).

3.3. Discussion

The basic idea behind workflow-specific adaptation and application-specific adaptation is to dynamically optimize the utilization of mobile resources for improved productivity. The need for the adaptations of resource assignment and item prioritization is based on the observation that the status of mobile resources (e.g., mobile workers who perform on-site work activities) may change constantly and the time (or cost) needed to complete an assigned activity is a function of resource status. The adaptation capabilities enable the seamless integration of mobile resources and application tools into workflow processes for field service applications (see Example 1). The adaptations of background pre-fetching and on-line fetching optimize the utilization of low and varying bandwidths for processing a series of workflow electronic documents (see Example 2).

The utilization of mobile resources is, however, realized in different ways by workflow-specific and application-specific adaptations. The workflow-specific adaptation performs the optimization by scheduling and sequencing multiple work activities dynamically. The scheduling and sequencing take factors into account such as the resource load (e.g., the time needed to complete assigned activities or the available bandwidth for document pre-fetching) and the resource need for all work activities. The application-specific adaptation uses application semantics or user knowledge to optimize the effective utilization of mobile resource for each individual work activity. The two adaptation paradigms are, therefore, complementary to each other.

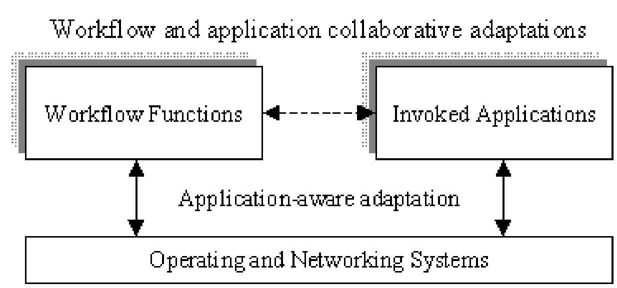

Figure 4. Collaborative adaptations

The collaboration capabilities of two adaptation paradigms are also important, as workflow functions (or invoked applications) might need to adapt to not only the change of resource status that is managed by operating and networking systems, but also the change of resource status specific to individual applications (or workflow functions). For example, the pre-fetching strategy could collaborate with the on-line fetching strategy to decide what type of data should be pre-fetched and at what quality level the data are pre-fetched. In essential, this collaboration decides the bandwidth utilization and allocation by using application and workflow semantics (not just based on physical bandwidth availability).

The collaboration between workflow functions and invoked applications has a different emphasis from the collaboration between an operating system and individual applications for the application-aware adaptation in Odyssey [8]. The former strives to achieve the effective utilization of mobile workflow resources by using application and workflow semantics. In contrast, the latter enhances the adaptation capabilities of multiple concurrent and independent applications by monitoring and allocating mobile resources at the operating system level. From the operating (and networking) system point of view, both workflow functions and invoked applications are application level programs. Therefore, both of them could be implemented by following the application-aware adaptation paradigm proposed in [8]. Figure 4 sketches the relationship between the two types of collaborative adaptations.

Finally, it is interesting to notice that the adaptation paradigms described above could further strengthen the advantages and benefits of workflow-based applications over conventional applications in terms of the utilization of mobile computing and human resources. One of the thrusts of converting conventional applications into workflow-based applications is to improve workers' productivity by optimizing the utilization of resources through activity scheduling and sequencing. Our work here extends the advantages and benefits in mobile environments.

4. Related Work

Application-specific adaptation has been identified as an effective way to support mobile applications and experienced in several previous projects, including Coda [7], Odyssey [8], Rover toolkit [6], and MOST [3] etc. Application-specific adaptation can be implemented by adding mobile-awareness into individual applications (e.g., those in the Odyssey and Rover projects) or providing application extensions or utilities (e.g., the application-specific resolvers in Coda). Furthermore, mobile-aware applications can either take the entire responsibility for the adaptation or collaborate with the operating system that monitors mobile environments and enforces resource allocation to make the decision of adaptation (e.g., the application-aware adaptation in Odyssey [8]).

Mobile resource management and assignment is related to work in context-aware computing [10,11]. In the Active Badge application [11], staff (a mobile resource) wearing badges can have telephone calls (i.e., work activities) directed to their current location. But the Active Badge project did not address the adaptation issues for weakly connected or disconnected resources. The UI techniques for proximate selection [10] can be used for the design of worklist windows for item prioritization.

Some previous work has addressed the issues about disconnected operations for workflow applications [1,2,4]. In [5], we have discussed the role of workflow-specific adaptation in dealing with the bandwidth constraints for the document processing. There are a few recent proposals about "adaptive workflow" from the workflow community [9]. However, the scope in these proposals is different from that of the workflow-specific adaptation. In "adaptive workflow", the approach is to dynamically change the definition of workflow process for each workflow instance. Workflow-specific adaptation advocates the adaptation of workflow run-time functions or utilities that does not require changing the definition of a process (or instances of a process). Though the "adaptive workflow" approach can be useful to deal with the dynamics of mobility, some complicated issues such as integrity, correctness, and administration of process remain unclear and unsolved.

5. Conclusion

In this position paper, we describe application examples that can benefit from mobile computing and workflow management technologies. We identify application-specific adaptation and workflow-specific adaptation as two adaptation paradigms supporting mobile workflow applications. We put forth the view that the complementary and collaborative capabilities offer improved mobile solutions for workflow applications. A prototype implementation for the proposed adaptive strategies is under way.

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References

[1] Alonso, G. etc., "Exotica/FMDC: Handling Disconnected Clients in a Workflow Management System" in Proceedings of 3rd International Conference On Cooperative Information Systems, Vienna, May 1995.

[2] Bubler, C. "User Mobility in Workflow Management Systems", in Proceedings of the Telecommunication Information Networking Architecture Conference (TINA95), Melbourne, Australia, Feb. 1995.

[3] Davies, N., Blair, G. S., Cheverst, K., and Friday, A., "Supporting Adaptive Services in a Heterogeneous Mobile Environment", in Proceedings of 1st IEEE Workshop on Mobile Computing Systems and Applications, Dec. 1994.
[4] Hesselman, M., Irmscher, K. and Mittasch, C., "Mobile Users in Workflow Management Applications", in Proceedings of 2nd Workshop on Personal Wireless Communications, Frankfurt am Main, Germany, 1996.
[5] Jing, J, and Huff, K., "Adaptation for Mobile Workflow Applications", in Proceedings of Workshop on Modeling and Simulation in Wireless Systems, Montreal, Canada, July 1998.
[6] Joseph, A. D., Tauber, J. A. and Kaashoek, M. F., "Mobile Computing with the Rover Toolkit", IEEE Transactions on Computers: Special issue on Mobile Computing, Vol. 43, No. 3, March, 1997.
[7] Kistler, J. J. and Satyanarayanan, M., "Disconnected Operation in the Coda File System", ACM Transactions on Computer Systems, Vol. 10, 1992.
[8] Noble, B., Satyanarayanan, M., Narayanan, D., Tilton, J. E., Flinn, J., Walker, K., "Agile Application-Aware Adaptation for Mobility", in Proceedings of the 16th ACM Symposium on Operating System Principles, St. Malo, France, Oct. 1997.
[9] Sheth, A. and Kochut, K. J., "Workflow Applications to Research Agenda: Scalable and Dynamic Work Coordination and Collaboration Systems", in Advances in Workflow Management Systems and Interoperability, NATO Advanced Study Institute, August 1997.
[10] Schilit, B. N., Adams, N., and Want, R., "Context-Aware Computing Applications", in Proceedings of 1st IEEE Workshop on Mobile Computing Systems and Applications, Dec. 1994.
[11] Want, R., and Hopper, A., "Active Badges and Personal Interactive Computing Objects", in IEEE Transactions on Consumer Electronics, 38(1), Feb. 1992.