Control Methods for Wireless-mesh-network Link-scheduling Adaptive to Traffic Changes and Application Selection Adaptive to User Activities

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1. **S. Kurakake**, Y. Ogiri, and H. Nakano, "An adaptive link scheduling by graph coloring for wireless mesh networks with partial traffic observation capability,"IEICE Transactions on System and Information, Apr. 2011 (Conditionally accepted) (in Japanese).

2. **S. Kurakake**, K. Yamazaki, and K. Imai, "Real-World-Oriented Service Platform Based on the Task Model," IEEE Communications Magazine, pp.72-78, Sept. 2006.

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1. **S. Kurakake**, and T. Naganuma, "A framework of task-based service selection support for mobile Internet and ubiquitous networks," Proc. IASTED Int. Conf. Artificial Intelligence and Applications: AIA2005, pp.521-526, Feb. 2005.

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Preface

The development of wireless communication network technology and information processing technology have contributed to the proliferation of mobile applications, that have changed the way of life of ordinary people of today. These applications assist people in many aspects of life including social life, purchase, transportation, education, money management, and enjoining entertainment. These applications are expected to enhance their performance and function so that the applications can assist people at much more aspects of life. Then systems and networks that support and provide these applications have to deal with the environment where users of the enhanced applications, and the networks and the systems that support the enhanced applications are surrounded. Therefore a method to control the behavior of an application, a network, and a system to have them adapt to conditions of the environments is inevitable. Building control methods for new environments, possibilities and constraints of that are not well known, becomes very important especially when conventional wireless networks or systems do not meet the requirements of the environments , and thus is set as the goal of the thesis.

Basic strategy for the building of our control method is first to construct a generic model representing environment conditions that applications, networks and systems are related to, then to establish the way to explore the effect of the change in conditions of surrounding environments on the applications, the networks, and systems, and to derive a guideline for the control method of the applications, the networks, and the systems.

As a first step to build a control method of wireless network adaptive to changes in conditions for varieties of environments, traffic load was focused as primal condition of environment. The impact of traffic load changes and the restriction of traffic load observation on the network performance were examined. We proposed a method for a link scheduling of a wireless mesh network that adapts to the change of average traffic demands at communication links. This method is based on a weighted graph coloring and we came up with new weight updating procedure to adapt to traffic demands change. We conducted data transmission simulations where traffic demands at randomly selected communication nodes increase to compare the adaptability of the proposed method and conventional methods to traffic demands increment. The upper bound of traffic demands increment where all data were successfully transmitted to destinations was investigated as an indicator of the throughput of the network. The upper bound is dependent on the percentage of nodes that increase traffic demands. When the percentage of nodes that increase traffic demands grows, the upper bounds decrease for the proposed method and an non-adaptive conventional method, however, the ratio of the upper bound of traffic demands increment of the proposed method to that of the non-adaptive conventional method were kept around 200% for all percentages. It is concluded that the proposed method acquired significant adaptivity for traffic demands increment compared to conventional methods. The effect of the restriction of traffic demands observation to limited nodes was also investigated. We examined the upper bounds of traffic demands for networks designed by the proposed method with four different types of traffic load observation restriction. All restricted networks did not show the adaptability when the percentage of the number of observable nodes is low, however as the percentage grows, the ratio of upper bound of traffic demands of each method to that of the non-adaptive method reaches 121% to 174%. Among the restrictions, the restriction to nodes with large traffic demands at initial time showed the superiority for most cases. Instead the restriction to nodes with complex network topology such as nodes connected to many communication links had network topology dependent disposition and did not achieve good performances in general. As a conclusion, the observation restriction to nodes with large traffic should be adopted if a restriction on the number of observable nodes is imposed for network implementation.

Context-aware application selection system has been focused as the target of our control method for application layer. Semantic model to describe user activities has been constructed to use for the selection of an application appropriate for a user activity. We treats a user activity as the performance of tasks necessary for solving a problem that the user encounters. The representation of a task of solving a large problem are decomposed into the representations of sub-tasks of solving the sub-problems decomposed from the large problem. Task itself is represented by task concept and its method using vocabulary of task ontology. Description of user activity model starts from the task at the level of large granularity. Next, methods to achieve the task are linked, and each of the methods is decomposed into a sequence of sub-tasks. This process continues until the granularity of task concepts reaches the granularity of available applications. The user activity model also features that it includes prevention tasks that prevent obstacles from happening, and solution tasks to solve the problems which have happened. We constructed generic user activity model that contains hundreds of general task concepts. We build instance level user activity model for a specific facility from the generic user activity model. This leverage the generic user activity model so that we can populate several thousand specific model relatively low cost with very few contradiction. An application is associated with an appropriate task concept in the instance model. Applications are considered methods to accomplish associated task concepts.

It also becomes possible to use sensor data to detect some of instance level user activity. In this manner, our user activity model consists of generic user activity model and instance level activity models, and this enables both the wide coverage of user activity representations and sensor triggered semi-automated processing at the same time. This is the original feature of our user activity model.

Based on the user activity model we built application selection schema. A given target task is matched to the task concept in the user activity model, the matched task concept is decomposed to sub-tasks through a method selected in terms of the invocation possibility by users at given user activity, and applications associated with task concepts are presented as selected applications.

The method was applied to build a prototype of context-aware information delivery system for consumer in a real commercial facility. We constructed the instance user activity model that has more than 3000 rules. The prototype was used for a trial service provided for a real department store. About 700 customers joined the trial and their evaluation results indicate that the instance model is successfully constructed and the model construction method is valid.

The contribution of this thesis is the control methods based on the generic model of environment conditions that enables the investigation of the effect of environment conditions to an application, and an network and/or a system that support the application. Because of the generic model, the methods are very effective especially for new applications in new environments where conventional applications or networks are not supported.

Research on wireless mesh network adaptive to traffic load has been conducted while the author belongs to Graduate School of Information Science and Technology, Osaka University. Research on context-aware application selection system adaptive to user activities was conducted at NTT DOCOMO and DOCOMO communications laboratories USA, Inc. Combining both research results, this thesis shows common strategy that works for building control method in the areas from network layer to application layer.

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1 Introduction

1.1 The goal of the thesis

The development of wireless communication network technology and information processing technology have contributed to the proliferation of mobile applications, that have changed the way of life of ordinary people of today. These applications assist people in many aspects of life including social life, purchase, transportation, education, money management, and enjoining entertainment. It is realized that people from all over the world use the same application and communicate and collaborate with people from world in real time. It is already common that people get information of what has happened in very distant places in minutes. These applications are expected to enhance their performance and function so that the applications can assist people at much more aspects of life by, for example, providing people solutions to problems encountered in life, supporting always-on connectivity to more people in closer fashion, and allowing people to get more information in less time. The creation of new applications that assists people in new aspects of life may require new wireless network technologies and new system technologies, and demand new ways of using conventional technologies. For this purpose, it is required to explore possibilities and constraints of environments of the new aspects of life, and understand the effect of environment conditions on the behavior of applications, and networks and systems that support the applications. A control method of the behavior of applications, networks and systems based on such understanding of the surrounding environments is inevitable. Therefore building such a control method for new environments becomes very important especially when conventional applications have not been used in the environments, and thus is set as the goal of the thesis.

Basic strategy for the building of our control method is first to construct a generic model representing environment conditions that applications, networks and systems are related to, then to establish the way to explore the effect of the change in conditions of surrounding environments, and to derive a guideline for the control method of the application, the network, and the system. We aim to realize applications adaptive to environment condition changes. Toward the construction of systems and networks that support such applications, we conducted research on wireless mesh network link scheduling adaptive to traffic changes in the area of wireless communication and conducted research on application selection adaptive to user activities in the area of application layer in this thesis.

1.2 Background

In telecommunications and computer networks, a channel access method or a multiple access method allows several terminals connected to the same multipoint transmission medium to transmit over it and to share its capacity. A channel access method is based on a multiplexing method, that allows several data streams or signals to share the same communication channel or physical medium. Multiplexing is in this context provided by the physical layer. A channel access method is also based on a multiple access protocol and control mechanism, also known as media access control (MAC). This protocol deals with issues such as addressing, assigning multiplex channels to different users, and avoiding collisions. The MAC-layer is a sub-layer in Layer 2 (Data Link Layer) of the OSI model and a component of the Link Layer of the TCP/IP model.

Channel access methods can be divided into two groups. First group includes circuit mode and channelization methods such as time division multiple access (TDMA), frequency division multiple access (FDMA), wave division multiple access (WDMA), and code division multiple access (CDMA). The second group consists of packet mode methods including contention based random multiple access methods such as carrier sense multiple access with collision detection (CSMA/CD) and carrier sense multiple access with collision avoidance (CSMA/CA), token passing such as token ring, polling, and resource reservation packet-mode protocols such as dynamic time division multiple access (Dynamic TDMA). In the Telecommunications Handbook [1], the two groups are further divided into the three MAC categories shown in Table 1. Fixed assigned category includes TDMA, FDMA+WDMA, and CDMA. Demand assigned category includes Dynamic TDMA and Token Passing. Random access category includes CSMA/CD, and CSMA/CA.

In methods categorized into random access, a data transmission request from a terminal connected to a channel is accepted if any of other terminals are not transmitting data over the channel. Then, all the channel resource is allocated to the terminal. This means that random methods do not estimate traffic load required to transmit data at each terminal in advance, or do not arrange terminals that have data to transmit at the same time so as to share the channel. Traffic load required to transmit data at each terminal is called traffic demands in this thesis. The methods can deal with burst transmission, traffic demand of which is not known in advance, however, the channel efficiency becomes lower drastically with more competing terminals with traffic demands [20]. WiFi uses a method in random access.

Methods in demand assigned category use a signal called a token or make

Table 1: MAC categories

Fixed assigned		TDMA, FDMA+WDMA, CDMA
Demand assigned	Reservation	Dynamic TDMA
	Polling	Token Passing
Random access		CSMA/CD, CSMA/CA

a reservation to authorize a node to transmit. The node that obtained a token or made reservation can transmit all data the node demands to transmit. The advantage over random access is that collisions are eliminated, and that the channel bandwidth can be fully utilized without idle time when demand is heavy. The disadvantage is that even when demand is light, a node wishing to transmit must wait for the token or the reservation, and this increases latency.

In methods categorized into fixed assigned, the traffic demands at each terminal is estimated or assumed, and the channel resource is shared by terminals with traffic demands at the same time under the control of a centralized controlling node or distributed controlling nodes. These methods can keep the channel efficiency high at circumstance where many terminals have traffic demands at the same time. This method is used by Cellular phone system and WiMAX system that are required to use wireless resource with high efficiency. Research on graph coloring based link scheduling [3],[4],[5] shows that TDMA link scheduling can make throughput close to the link capacity if the traffic demand at each terminals and the interference model are known in advance.

Thus suitable wireless access method can vary depending on the accuracy of the estimation for the traffic demands at terminals, and the efficiency of the utilization of wireless resource will vary as a result. Therefore, it is very important to develop a method that can investigate how accurate it is possible to estimate traffic demands for a network which an newly developing application will use, how much the accuracy affects the network performance, and what are relevant requirements the application or its environment has for the estimation accuracy of traffic demands for the network. An appropriate access method should be selected using such a method, then the network based on the selected access method should be designed.

In addition to traffic load of communication links, network topology and error rate of communication links are important network related conditions. Density of communication nodes, disposition of communication nodes, restrictions for the number of hops, and other conditions regarding network topology affect the performance of a network. Even if network topology and traffic load of each communication links are fixed, error rate of communication affect the network performance significantly. High error rate of communication links requires measures for extra error compensation, frame length adaptation, and retransmission. Network should deal with such network related conditions. For that purpose, the effect of the changes in such network related conditions on the network performance should be investigated. Then a control method of the behavior of network base on the investigation should be built in order to realize a network that deals with changes in conditions of environments.

If a computer system or a communication system varies its behavior depending on the change of environment surrounding the system, the information related to the surrounding environment is called context and such a system is called a context-aware system. Context-aware system has been studied, and many prototypes have been implemented for years[36],[38],[39],[40]. Popularity of context-aware computing research indicates that a system that can adapt its behavior to user and surrounding environment has a profound potential to provide much more user-specific services. Context awareness is especially relevant to mobile and ubiquitous applications because some of those applications are designed to be provided only at limited time and/or locations for users in a specific situation. Time, location, identity and activity have been proposed as the primary element of context[37]. Because time and location are easily detected, a lot of location-aware systems such as guides for city tours[38],[39] and guides for museums[40], have been designed. Activity is much more difficult to detect, but some aspects of activity can be detected by placing sensors equipped in the environment. Advanced context-aware applications using activity context information are realized for a smart environment[41]. Prior research prototypes tend to focus on specific applications in specific environments. The goal, however, is for users to be assisted in varieties of aspects of life. In order for context-aware applications to expand their applicable domain, the applications should be able to understand wider ranges of application related environment conditions deeper and handle them more systematic way so that the application can adapt to environment conditions of expanded domains.

In Table 2 we made a list of applications associated with most relevant system function and conditions that affect the behavior of the system components or that the system components refer to. Context used in context-aware system research literature is location, identity, activity, time[35], user&role, process&task, and device[34]. Typical network related conditions are traffic load, channel bit error rate of a communication link, and devices used for communication. These conditions have impact on the behavior of an application and network . Here the behavior of an application does not necessarily means the behavior of a single client application. Searching an appropriate application

Table 2: Application samples associated with relevant system components and influential conditions

Function	Condition	Application
Mash up, Composition	Traffic load	A1: Congestion dependent communication medium
Mash up, Composition	Error rate	A2:Error rate dependent communication medium
Mash up, Composition	User activity, User task	A3:Travel planner
Search	Traffic load	B1:Congestion dependent search
Search	Error rate	B2:Error rate dependent search
Search	Location	B3:Location time based search
Search	Contents	B4:Indexing
Parameter tuning	Time	C1:Time sensitive notification
Parameter tuning	User & Role	C2:User interface adaptation
Parameter tuning	Others	C3:Disaster relief
Transport	Traffic load	D1:TCP window size
Transport	Error rate	D2:AMC
Transport	Others	D3:Disaster relief

among huge numbers of applications available through the Internet depends on these conditions too. Furthermore, mash up mechanism for web systems and intent mechanism for Android applications enable the composition of applications available over the Internet to realize necessarily function and this process is also dependent on these conditions.

A1 to select appropriate communication medium from VOIP, instant messaging, stored voice, text messaging, and P2P information delivery depending on the average congestion level of the network

A2 to select appropriate communication medium from VOIP, instant messaging, stored voice, text messaging, and P2P information delivery depending on the average error rate of the network

A3 to make travel plan with reservation of transportation, accommodation and restaurant necessary to make business trip by selecting and composing relevant applications in the Internet

B1 to select appropriate communication tools from the Internet depending on the average congestion level of the network

B2 to select appropriate communication tools from the Internet depending on the average error rate of the network

B3 to search restaurant navigation applications that covers only specific areas. to search applications usable at night

B4 to search application that assist user's activities

C1 to notify a user when appointed time is approaching at a bank or a hospital.

C2 to enlarge font size of the application if elderly person is using it

C3 to lower the level of authentication so that more people effected by a disaster can use the application

D1 to widen TCP size if the amount of data to send grows

D2 to match the modulation, coding and other signal and protocol parameters to the conditions on the radio link (called Adaptive Modulation and Coding).

D3 to heighten the upper limit of the number of users that can use the application at the same time so that more people effected by a disaster can send a message through a network

Table 2 shows the variations of the effect of conditions on system components. Conventional applications are tend to work only very limited range of relevant conditions, however, new applications may require to handle with conditions that is not supported by conventional applications. Thus building control methods of the behavior of applications to adapt wider range of conditions is very valuable for effective development of applications affected by surrounding environments of expanded applicable domains.

1.3 Network related conditions of environments

Network topology, traffic load and bit error rate of communication links are treated important conditions among varieties of network related conditions. Density of communication nodes, disposition of communication nodes, restrictions for the number of hops, and other conditions regarding network topology affect the performance of a network. Once topology is decided, traffic load and bit error rate of communication links also affect the network performance. The effect of the changes of such conditions on the realized network throughput should be investigated, and then a control method of the behavior of network base on the investigation should be built in order to realize a network that deals with changes in network related conditions of environments.

As described in section 1.2 suitable architecture of wireless access method varies depending on the estimation accuracy for traffic load. However, estimation methods of traffic load have not been established or the effect of the uncertainty of the estimation on the network performance has not been investigated. Issues to investigate how accurate it is possible to estimate traffic demands for a network which an newly developing application will use, how much the accuracy affects the network performance, and what are relevant requirements the application or the environment has for the estimation accuracy of traffic demands for the network are first to be solved to decide adequate architecture. The effect of network topology and error rate of communication links are to be treated for the decided architecture of access method, Thus as a first step to build a wireless network adaptive to changes in conditions for varieties of environments, traffic load was focused as primal condition of environment. Issues related to network topology and error rate of communication links are remained for future works.

We built our method on TDMA/TDD based multihop wireless mesh networks [6],[7]. TDMA mesh network is expected to be used for new application field because it can be flexibly deployed with relatively low cost for new environment. The multihop wireless mesh network is called relay network in IEEE 802.16[22]. The semi-optimal solutions of link scheduling for a wireless mesh network can be obtained by applying graph theory with the assumption that traffic load of communication links and interference model are given. Then we can investigate the effect of varying traffic load on the semi-optimal solutions. This is the reason that we used a wireless mesh network to study a generic model of the effect of traffic load on wireless network performance.

The application of graph coloring theory to link scheduling of mesh networks has been studied to the obtain optimal link schedule [2],[3],[4],[13]. The smallest number of colors needed to color a graph is called chromatic number. A conflict graph of a communication network is a graph where nodes represent communication links and edge is connected between nodes corresponding to communication links interfering each other. The chromatic number of a conflict graph is the minimum frame length of a corresponding communication network. The finding of chromatic number for given graph is NP-hard problem, therefore, a number of heuristic methods that give solution close to the optimal one for link scheduling of wireless mesh network have been proposed [4],[13]. There are the following open problems for those heuristic methods.

1. Comparison on performance such as throughput and the evaluation of computational complexity to obtain link schedules have been conducted with the assumption that the average traffic load of each link and interference model among links are known in advance. A systematic investigation for the case that actual traffic load is different from estimated traffic demand at each link is not well studied.

2. It is known that weighted graph coloring [18],[19] gives better solutions for the case the average traffic load of each link is not the same. There is still no theory on how to calculate the weight of links when the average traffic load is changed.

3. Observation of traffic load at each communication link may cost the computation of observation at a communication node connected to the communication link. It is possible to set a traffic observation device in order to reduce the computation cost of the communication nodes. Such a extra device causes extra expense. Transmission of data regarding observed traffic load to a controlling node needs bandwidth, and this affects the performance of the network. It is desirable if the observation is restricted to limited communication nodes while keeping network performance in order to reduce the cost mentioned above. It is necessary to establish a method that explore the impact of non-observable links on the network performance especially when the traffic demands of links are changing.

These open problems gives issues for our control method. In this thesis, we studied the effect of traffic load change on the network performance and the effect of the restriction of traffic load observation in addition. We proposed a method to control link scheduling of a wireless mesh network that adapt to the change of average traffic load of communication links. We demonstrated the evaluation of the effect of average traffic load change to the semi-optimal throughput. The evaluation shows the proposed method realize an adaptive link scheduling throughput of that is about twice better than those of non-adaptable link scheduling methods in the conducted simulation. We also investigated the effect of the restriction of traffic load observation to limited nodes. We exhibited the evaluation of the effect of four different types of restrictions. Among the restrictions, the restriction to nodes with large traffic demands at initial time showed the superiority for most cases. Instead the restriction to nodes with complex network topology such as nodes connected to many communication links had network topology dependent disposition and did not achieve good performances in general. As a conclusion, the observation restriction to nodes with large traffic should be adopted if a restriction on the number of observable nodes is imposed for network implementation.

1.4 Application related conditions of environments

Context-aware computing has been a popular research area, and many context-aware services have been proposed and demonstrated. Although they are designed to assist users in the real world, they support only a limited number of user activities. A location-based restaurant guide, for example, is useful for obtaining a list of restaurants near the user's current location. While it may adjust the listing based on the user's food preferences and previous dining experiences, the user must still choose an appropriate restaurant from the list by taking into account factors not directly related to dining. For example, if the user's purpose in visiting a restaurant is to meet colleagues, then restaurants suitable for a business meeting are more appropriate. Moreover, if the colleagues are on their way to the airport, the top priority may be the ability to arrange for a taxicab to take the colleagues from the restaurant to the airport after the meeting. In short, location-context assistance can support a user's activities to only a certain extent. A function must be added to the restaurant guide that can understand a wide variety of user activities as well as the dependency between the requirements for an appropriate restaurant and user activities before, during, and after dining. Simply enhancing context-awareness by using additional context will not provide these capabilities. Thus the applicable domain of a context-aware system can be very limited without the understanding of user activities. In addition to these drawbacks, conventional context-aware system that was designed to fit with a specific state of condition can not follow the change of condition state.

In order to overcome these difficulties, it is necessary to construct the deep understanding of a wide varieties of application related conditions and find a way to associate each state of the conditions to appropriate application parameters to adapt to the conditions and to follow the change of those condition state. Among application related conditions selected are user activities for the primal target of our research. This is because most of applications are designed to provide functions and information to users and thus their behavior are expected to meet user's needs. Issues for building control methods of the behavior of application adaptive to user activities are the construction of the deep understanding of a wide varieties of user activities and the development of a method to control application behavior according to the state of user activities.

From the view point of applications designed to work for users, user activities can be understood as solving problems to satisfy user's needs and to realize user's wants. To solve a difficult problem, it is common manner to divide the problem to smaller problems that are easier to handle with. Likewise a more general user activity corresponding to solving a large problem is decomposed into a more concrete user activities corresponding solving smaller problems decomposed from the large problems. It is very important observation that there are different generality levels among concepts of user activities. This means some activity concepts are considered to be parts of other concepts. This observation lead us to construct hierarchical structure of concepts of user activities. We call this user activity model, and our control method use this task model to control an application to adapt to a wide varieties of user activities and changes of user activities.

The difficulties to build such a user activity model is comprehensiveness of its coverage and consistency with in the model. Most of previous research on the construction of user activity models are sensor centric. This means that their models represent human behavior in terms of captured sensing data [49],[50],[51],[52],[53]. Because the expressiveness of sensing data is usually limited, their models represent only limited aspect of user activity.

Comprehensive semantic level model of user activities are necessary and related previous research are found in the area of knowledge representation (KR) [47]. KR research involves analysis of the way to use a set of symbols to represent a set of facts within a knowledge domain and the way to accurately and effectively reason. A key parameter in the construction of a KR is its expressivity. If a KR is more expressive, it is easier and more compact to express a fact or element of knowledge within the semantics of that KR. However, more expressive representations are likely to require more complex logic and algorithms to construct equivalent inferences. A highly expressive KR is also less likely to be complete and consistent. Less expressive KRs may be both complete and consistent.

In computer science, particularly artificial intelligence, a number of representations have been devised to structure information. KR is most commonly used to refer to representations intended for processing by computers. Representing knowledge in such explicit form enables computers to draw conclusions from knowledge already stored. Major projects attempted to encode wide bodies of general knowledge. Through such works the difficulty of KR came to be perceived. Then a number of ontology have been developed with huge efforts.

If we can restrict the target of ontology for user's tasks that can be solved by computer applications, it is feasible to build good ontology that covers those user activities. Then semantically appropriate applications can be selected for given user's task based on them. Research activities has been continued and produced general purpose ontology representing user tasks [42],[43],[44],[45],[46].

We built our control method based on a user activity model based on the research of generic task ontology mentioned above. Our user activity model has sufficient expressiveness to support a wide variety of application related user activities. In the model a user activity is represented as the performance of a series of tasks for solving a problem that a user or a system encounters. Based on the user activity model, the associations of applications to appropriate user tasks are constructed. The control of application selection is realized by selecting user task in the associations. Because a generic user activity model is based on well organized generic task ontology, instance level user activity model for a specific domain can be easily and effectively constructed from the generic user task model and accordingly the instance level of association of applications to instances of user tasks. Thus the control methods are a collection of the associations between user tasks and applications, and the feature of the way to construct the control methods is that it can create huge numbers of associations at relatively low cost and with very few contradictions.

1.5 Thesis organization

The organization of this thesis is as follows.

- Chapter 1 introduces this thesis and discusses the importance of adaptivity to condition changes in environments where applications, and networks and systems that support the applications are provided. Background and issues for wireless network and for context-aware systems are summarized.

- Chapter 2 shows research on wireless mesh network adaptive to traffic load changes. A weight graph coloring based link scheduling method that can adapt to traffic load change is proposed. The method is used to explore the effect of traffic load on the throughput of the network. The effect of traffic load observation restriction on the network throughput is also investigated.

- Chapter 3 shows research on context-aware system that can handle with varieties of user activities. A method to construct a model of user activities in semantic level is proposed. Then, a control method for application selection depending on user activities is constructed based on the model. A prototype system of user activity aware information delivery for consumer in commercial facilities and its trial results are stated in this chapter.

- Chapter 4 concludes this thesis.

2 Control method for wireless mesh network link scheduling adaptive to traffic changes

2.1 Wireless network issues related to conditions of environments

In telecommunications and computer networks, a channel access method or a multiple access method allows several terminals connected to the same multipoint transmission medium to transmit over it and to share its capacity. A channel access method is based on a multiplexing method, that allows several data streams or signals to share the same communication channel or physical medium. Multiplexing is in this context provided by the physical layer. A channel access method is also based on a multiple access protocol and control mechanism, also known as media access control (MAC). This protocol deals with issues such as addressing, assigning multiplex channels to different users, and avoiding collisions. The MAC-layer is a sub-layer in Layer 2 (Data Link Layer) of the OSI model and a component of the Link Layer of the TCP/IP model.

Channel access methods can be divided into two groups. First group occludes circuit mode and channelization methods such as time division multiple access (TDMA), frequency division multiple access (FDMA), wave division multiple access (WDMA), and code division multiple access (CDMA). The second group consists of packet mode methods including contention based random multiple access methods such as carrier sense multiple access with collision detection (CSMA/CD) and carrier sense multiple access with collision avoidance (CSMA/CA), token passing such as token ring, polling, and resource reservation packet-mode protocols such as dynamic time division multiple access (Dynamic TDMA). In the Telecommunications Handbook [1], the two groups are further divided into the following three MAC categories. Fixed assigned category includes TDMA, FDMA+WDMA, and CDMA. Demand assigned category includes Dynamic TDMA and Token Passing. Random access category includes CSMA/CD, and CSMA/CA.

In methods categorized into random access, a data transmission request from a terminal connected to a channel is accepted if any of other terminals are not transmitting data over the channel. Then, all the channel resource is allocated to the terminal. This means that random methods do not estimate traffic load required to transmit data at each terminal in advance, or do not arrange terminals that have data to transmit at the same time so as to share the channel. Traffic load required to transmit data at each terminal is called traffic demands in this thesis. The methods can deal with burst transmission, traffic demands of which is not known in advance, however, the channel efficiency becomes lower drastically with more competing terminals with traffic demands [20]. WiFi uses a method in random access.

Methods in demand assigned category use a signal called a token or make a reservation to authorize a node to communicate. The node that obtains a token or a reservation can transmit all data the node demands to transmit. The advantage over random access is that collisions are eliminated, and that the channel bandwidth can be fully utilized without idle time when demand is heavy. The disadvantage is that even when demand is light, a node wishing to transmit must wait for the token, and this increases latency. In methods categorized into fixed assigned, the traffic demands at each terminal is estimated or assumed, and the channel resource is shared by terminals with traffic demands at the same time under the control of a centralized controlling node or distributed controlling nodes. These methods can keep the channel efficiency high at circumstance where many terminals have traffic demands at the same time. This method is used by Cellular phone system and WiMAX system that are required to use wireless resource with high efficiency. Research on graph coloring based link scheduling [3],[4],[5] shows that TDMA link scheduling can make throughput close to the link capacity if the traffic demand at each terminals and the interference model are known in advance.

Thus suitable wireless access method can vary depending on the accuracy of the estimation for the traffic demands at terminals, and the efficiency of the utilization of wireless resource will vary as a result. In addition to traffic load of communication links, network topology and bit error rate of communication links are important network related conditions. Density of communication nodes, disposition of communication nodes, restrictions for the number of hops, and other conditions regarding network topology affect the performance of a network. Error rate of communication links also affect the performance of networks. High error rate of communication links requires countermeasures for extra error compensation, frame length adaptation, re-transmission, and so on, that affect the network performance.

As described above suitable architecture of wireless access method varies depending on the estimation accuracy for traffic load. However, estimation methods of traffic load have not been established or the effect of the uncertainty of the estimation on the network performance has not been investigated. Issues to investigate how accurate it is possible to estimate traffic demands for a network which an newly developing application will use, how much the accuracy affects the network performance, and what are relevant requirements the application or the environment has for the estimation accuracy of traffic demands for the network are first to be solved to decide adequate architecture. The effect of network topology and bit error rate of communication links are to be treated for the decided architecture of access method, Thus as a first step to build a wireless network adaptive to changes in conditions for varieties of environments, traffic load was focused as primal condition of environment. Investigation of the effect of bit error rate of communications links and network topology on the network performance is remained for future works. Graph coloring based link scheduling can be used as a basis for such a method. Because it realizes network throughput close to link capacity, the effect of traffic demand change on the semi-optimal throughput can be investigated.

We build our method upon TDMA/TDD based multi-hop wireless mesh networks [6],[7]. TDMA mesh network is expected to be used for new application areas because it can be flexibly deployed with relatively low cost for new environments. The multi-hop wireless mesh network is called relay network in IEEE 802.16 [22].

TDMA is a channel access method for shared medium networks. The time is divided into slots of fixed duration, which are grouped into frames. Let the duration of each slot be T_s seconds and the total number of slots in a frame be N_f, then the frame duration called a frame length T_f is $T_f = N_f T_s$ seconds. The first N_c slots of the frame are called the control sub-frame and reserved for control traffic, while the last N_d slots for the frame are called the data sub-frame and reserved for data traffic. Here $T_f = N_c T_s + N_d T_s$. Communication nodes exchange messages in the control frame to negotiate a link schedule in the data sub-frame. A link schedule for a link l of a network is a list of assigned time slots in the data sub-frame the link could send packets. Here slots are synchronized among all links. The schedule repeats in every frame until the schedule is changed. The number of slots assigned to a link is called a weight of the link. If non of two links assigned to the same time slot causes interference, the schedule is interference-free. A interference-free schedule allows multiple nodes to share the same transmission medium while using only a part of its channel capacity. Each node transmit using assigned time slots of its link.

A wireless mesh network is a communication network made up of radio nodes organized in a mesh topology. Wireless mesh networks often consists of mesh clients, mesh routers (MRs) and gateways(GWs). A GW is connected to wired networks. The mesh clients are often laptop PCs, cell phones, sensor devices with radio communication capability to a near-by MR. A MR forwards traffic to and receives traffic from other MRs and GWs. Each MR must not only capture and disseminate data of its own mesh clients, but also serve as relay for other MRs. Data propagates along a path by hopping from node to node until the destination is reached.

The network performance of wireless mesh networks depends on multiple gateway association to communication nodes [8],[9],[10] and link scheduling [11],[12],[13]. The gateway association associates each MR with a GW, and the link scheduling assigns each link of the network a link schedule. By centralized mechanism for link scheduling, one controlling node obtain information about traffic demand at each communication node and interfere model among links, decides a link schedule for each link, and notify the link schedule to each link. By distributed mechanism for link scheduling, distributed controlling nodes capture information regarding traffic demands of neighbor nodes and interference models for them, decides link schedules of neighboring nodes, and notify the link schedules to the neighboring nodes.

The frame length of a link schedule affects the overall throughput of the network. If traffic load of each link is the same, the minimum frame length means maximum throughput. In addition to the frame length, other factors including the header size of physical layer and MAC layer, bit error rate, routing protocol, and hardware processing power for packet transfer of network routers have impact on the throughput of the network. We takes only frame length into account as a first step, and add other factors later on. Then assuming dynamic frame length, the objective of link scheduling is to find a interference-free link with minimum frame length.

The application of graph coloring theory to link scheduling of TDMA mesh network has been studied to obtain an interference-free link schedule for given traffic demands with the minimum frame length [2],[3],[4],[13]. The smallest number of colors needed to color a graph is called chromatic number. A conflict graph of a communication network is a graph where nodes represent communication links and edge is connected between nodes corresponding to communication links interfering each other. The chromatic number of a conflict graph is the minimum frame length of a corresponding communication network. The finding of chromatic number for given graph is NP-hard problem, therefore, a number of heuristic methods that give solution close to the optimal one have been proposed [4],[13]. There are the following open problems for those heuristic methods.

1. Comparison on performance such as throughput and the evaluation of computational complexity to obtain link schedules have been conducted with the assumption that the average traffic load of each link and interference model among links are known in advance. A systematic investigation for the case that actual traffic load is different from estimated traffic demand at each link is not well studied.

2. It is known that weighted graph coloring [18],[19] gives better solutions

for the case the average traffic load of each link is not the same. There is still no theory on how to calculate the weight of links when the average traffic load is changed.

3. Observation of traffic load at each communication link may cost the computation of observation at a communication node connected to the communication link. It is possible to set a traffic observation device in order to reduce the computation cost of the communication nodes. Such a extra device causes extra expense. Transmission of data regarding observed traffic load to a controlling node needs bandwidth, and this affects the performance of the network. It is desirable if the observation is restricted to limited communication nodes while keeping network performance in order to reduce the cost mentioned above. It is necessary to establish a method that explore the impact of non-observable links on the network performance especially when the traffic demands of links are changing.

Thus, the impact of traffic demands changes and the restriction of traffic load observation on the performance of a network designed by a graph coloring based link scheduling are yet to be investigated and link scheduling method should be improved so as to absorb as much as possible of the effect of the traffic change and the observation restrictions.

Different approaches, those are not based on graph coloring, for link scheduling of a wireless mesh network adaptive to changes in traffic demands and other conditions have been studied. [14] proposed a method to adapt control sub-frame time slots reservation according to traffic load, but the method does not control data sub-frame time slots assignment so as to maximize throughput of data. Dynamic sizing of frame length methods to improve throughput have been proposed [15], [16], [17]. They control the frame length against channel noise, or energy efficiency of a battery of a communication node. There are still possibility to control time slots assignment for the data sub-frame obtained by the methods in order to maximize throughput.

Assumption we made are that traffic load of links, and interference model among links are known in advance, and the traffic load would change. The objectives in this section are

- to build an adaptive link scheduling method that find a interference-free link schedule that maximizes the overall throughput of the network for changing traffic demands.
- to establish a method that explore the impact of non-observable links on the network performance especially when the traffic demands of links are changing.

Conventionally it is regarded as a feasibility evaluation to check if the link schedule that is the result of a link scheduling with all weight be equal is possible for the given frame length. It is regarded as the evaluation of optimal throughput to construct the link schedule with minimum frame length for given weights of communication links. Weight should be decided roughly proportionately to the traffic demands of its link. However quantization causes difference on the resulting network performance. More sophisticated weight calculation is necessary. We propose an adaptive link scheduling method that optimize the weight and minimize the frame length at the same time. This means our method can evaluate the feasibility and improve the throughput at the same time.

2.2 Link scheduling by using weighted graph coloring

Theoretical approach for link scheduling with minimum frame length has been studies as an application of graph coloring theory[2],[3],[4]. Vertex coloring is an assignment of labels traditionally called colors to the vertices of a given graph such that no two vertices sharing the same edge have the same color.The smallest number of colors needed to color a graph is called chromatic number, and the problem to find the chromatic number for given graph is called vertex coloring problem. A communication network is represented by a communication graph $G = (V, E)$, where $V = (v_1, \cdots, v_n)$ is the set of terminals and $E = (e_1, \cdots, e_n)$ is the set of possible directed communication links denoted by (v_i, v_j). A conflict graph F_G is used to represent the interference in G. Vertex $l_{i,j}$ of F_G corresponds to a directed link (v_i, v_j) in the communication graph G. There is an edge between vertex $l_{i,j}$ and $l_{p,q}$ in the conflict graph F_G if and only if (v_i, v_j) conflicts with (v_p, v_q). Link scheduling of a communication network is essentially equivalent to the vertex coloring of F_G. The vertex coloring problem is known to be NP-hard, and some heuristics for link scheduling have been proposed. Among them, we confirmed the method proposed in [4] showed good results when it is used for simulations. The method is as follows.

Algorithm 1

A communication graph $G = (V, E)$ is given.

Step1 Let the number of communication links be m, construct a conflict graph F_G, and set graph $G' = F_G$

Step2 If graph G' is not empty, go to Step3. If empty, go to Step4.

Step3 Find the vertex with the smallest total degree in G' and remove this vertex from G' and all its incident edges. Let l_k denote the $(m-k+1)$th vertex removed.

Step4 Process links from l_1 to l_m and assign to each l_k the smallest time slot not yet assigned to any of its neighbors in F_G

In algorithm 1, the maximum number of time slot assigned is the frame length of the link schedule. The frame length obtained by the algorithm 1 is smaller than the maximum node degree of the conflict graph in many cases.

A weighted graph coloring derive a link schedule that assign time slots depending on the traffic load of communication links. This is appropriate when average traffic load for each communication link is different each other. [4] proposed the following method that uses weighted graph coloring. Note that weight is positive integer.

Algorithm 2

Step1 Build the conflict graph F_G based on original graph G. Assign weight $w_{i,j}$ to vertex $l_{i,j}$ of the conflict graph.

Step2 Construct a new conflict graph F'_G from F_G as follows. For each vertex $l_{i,j}$ with weight $w_{i,j}$, create $w_{i,j}$ vertices, $l^1_{i,j}, l^2_{i,j}, \cdots, l^{w_{i,j}}_{i,j}$ and add them to F'_G. Add to graph F'_G the edges connecting $l^a_{i,j}, l^b_{i,j}$ for $1 \leq a < b \leq w_{i,j}$. Also add to graph F'_G an edge $l^a_{i,j}, l^b_{p,q}$ if and only if there is an edge between $l_{i,j}, l_{p,q}$ in graph F_G.

Step3 Run algorithm 1 on F'_G.

Step4 Assign link $l_{i,j}$ all the colors those are used by $l^k_{i,j}$ for $1 \leq k \leq w_{i,j}$ in F'_G.

Algorithm 2 assigns time slots of the number of weight. Note that weight is assumed to be given and how to decide the weight is not explained in the literature. The number of nodes of the new conflict graph in this algorithm is much larger than that of the original conflict graph, and this increases computational cost. A simplified method is to assign time slots, the number of those is equal to weight, to the corresponding link based on the result of algorithm 1.

2.3 Link scheduling adaptive to traffic load change

2.3.1 Weight calculation

This subsection shows the conditions required for the weight of a link to transmit data to send from MR through the link, and how to re-calculate the weight to adapt to traffic load change. Let frame length be T [s], the capacity per a time slot of link j be $C(j)$ [bits/slot], the number of time slots assigned to link j within the frame be $d(j)$. Then traffic load per second $e(j)$ [bits/slot] that can be transmitted through link j is described as the following equation.

$$e(j) = c(j)\frac{d(j)}{T} \tag{1}$$

Equation 1 is also valid for the case adaptive modulation and coding is used where $c(j)$ is decided based on SNR(signal to noise ratio).

Let traffic load to transmit data assigned to link j be $\alpha(j)$ [bits/s], then $e(j) \geq \alpha(j)$ is a necessary condition for the link to transmit the assigned data successfully. The number of time slots assigned to a link is the size of the weight assigned to the link in time slots assignment by algorithm 2. A necessary condition for the weight of a link is described by the following equation.

$$w(j) \geq \left\lceil \frac{T}{c(j)}\alpha(j) \right\rceil \tag{2}$$

Here, $\lceil \bullet \rceil$ is a ceiling function.

If the weight of each link satisfies equation 2, data assigned to each link is transmitted to the next link within a frame. Therefore, the following equation is hold. Here, let $\epsilon(i)$ be the number of hops from node i to the GW, $n(i)$ be the amount of data assigned to the node,m be total amount of data to transmit in the overall network, and average data transmission time be t_{ave}.

$$t_{ave} \leq \frac{1}{m}\sum_{i} n(i)\epsilon(i)T \tag{3}$$

This means average data transmission time of the network is bounded above by frame length T.

When average traffic demands $\alpha(j)$ changes, the network can transmit the new traffic demands with upper bound of average data transmit time minimum if weight of each link is re-calculated so that the weight satisfies equation 2 for new traffic demands.

Next, we shows a weight re-calculation procedure to deal with rapid traffic demands change. Here rapid traffic demands change means that relatively high-bandwidth transmission over a very short period of time may occur while traffic is very low for other period of time. If the rapid traffic demands change is happened, a procedure based on quantities that hold for the average of traffic load may not provide high performance. Therefore, we take a probability function $p(j)$[bits/s] of traffic demands into account instead of the average of traffic demands. Assume that time t_p required to transmit the traffic demands over a link and the probability function $p(j)$ the required traffic load follows satisfy the following equation.

$$t_p \leq \left\lceil \frac{p(j)}{w(j)c(j)} \right\rceil T$$

Here, $w(j)$, T are obtained by algorithm3 introduced in the next section assuming the traffic demands be $\alpha(j)$. If $p(j) \geq \alpha(j)$ at some time, link schedule decided based on the average traffic load $\alpha(j)$ takes extra multiple of frame length. If weight is set as $w(j) + \Delta w(j)$ when $p(j)$ is larger than $\alpha(j)$, time $t_p^2$to transmit the traffic demands $p(j)$ is calculated as

$$t_p^2 = (T + \Delta T) \left\lceil \frac{p(j)}{(w(j) + \Delta w(j))c(j)}) \right\rceil$$

can be smaller. Here $\Delta T \geq 0$, $\Delta w(j) \geq 0$ are assumed and let $T + \Delta T$ be the frame length for weight be set as $w(j) + \Delta w(j)$. This equation shows the average data transfer time is affected by the probability function $p(j)$. In most situation, the probability function of traffic demands is not known. A empirical method is as follows. Pick up a couple of values selected randomly around the average traffic load, and calculate time t_i required to transmit the traffic demands.

$$t_i = \sum_{t=t_{start}}^{t_{end}} \left\lceil \frac{p_t(j)}{w(j)c(j)} \right\rceil T$$

Here, let $p_t(j)$ be traffic load of link j observed at frame t, t_{start} be the frame to start this calculation, and t_{end} be the frame to stop this calculation.

It is known that if time slot assignments of links on the path from the origin of data to the destination are associated, data transmission time can be further reduced[24]. Here we do not assume such association mechanism. We also assume that network topology, interference relations and the average amount of traffic demands can be treated not to change compare to the time required for link scheduling processing.

2.3.2 Adaptive link scheduling

Algorithm 3 is the procedure for adaptive link scheduling by using weighted graph coloring. The most important feature of the algorithm is that the calculation require a weight of one link at time instead of combination weights of multiple links. This reduce computational complexity.

Algorithm 3

Step1 Set the weight of each link be 1 and construct a conflict graph, apply algorithm 1 the conflict graph, and calculate frame length T_0.

Step2 Find minimum a weight for each link that satisfies

$$\frac{w(j)}{T_0} > \frac{\alpha(j)}{c(j)}.$$

Her traffic demands for link j be $\alpha(j)$. Then, calculate frame length T_1.

Step3 Check if the following equation holds for each link.

$$\frac{w(j)}{T_1} > \frac{\alpha(j)}{c(j)}$$

If the equation does not hold for some links, replace the value of T_0 by T_1, then run step2. Otherwise, go to Step 4.

Step4 Calculate $\beta(j)$ for each link j.

$$\beta(j) = w(j) - T\frac{\alpha(j)}{c(j)}$$

Starting from the link that the value $\beta(j)$ is minimum, increment the weight value by one and check if the frame length with incremented weight does not change. Continue this until no weight can be incremented, and go to Step5.

Step5 Apply algorithm 2 to the conflict graph with the weight calculated at step4, and obtain a link scheduling.

Algorithm 3 is proved to provide the link schedule that realizes minimum frame length among link schedules obtained by algorithm 2 with any variations of weights. Let a set of weights for all communication links be $w_1(i), (i = 1, \cdots, m)$. Assume the set of weights satisfies equation2, and the frame length of the link schedule decided by algorithm 2 with the set of weights be T_1. If there is another set of weights $w_2(i), (i = 1, \cdots, m)$ so that the set of weights satisfies equation2, and $w_2(j) \geq w_1(j)$ for $j, (1 \leq j \leq m)$ and $w_2(k) = w_1(k)$ for all $k, (1 \leq k \leq m, k \neq j)$. Let the frame length of the link schedule obtained by algorithm 2 with the set of weights $w_2(i), (i = 1, \cdots, m)$ be T_2. Then $T_2 \geq T_1$ because frame length obtained by algorithm 2 is an increasing function of weights. Therefore it is proved that once a set of weights w_1 that satisfies equation2 is found, any set of weights some weights of that are greater than corresponding weights of w_1 do not realize smaller frame length link schedule. In Step 2 ,$w(j)$ is the minimum integer that satisfies the following equation.

$$\frac{w(j)}{T_0} > \frac{\alpha(j)}{c(j)}$$

Because frame length obtained by algorithm 2 is increasing function of weights, frame length T_1 obtained in step 3 satisfy $T_0 \leq T_1$, and the following equation holds.

$$\frac{w(j)}{T_0} \geq \frac{w(j)}{T_1}$$

Thus if the following equation holds,

$$\frac{w(j)}{T_1} > \frac{\alpha(j)}{c(j)}$$

then $w(j)$ is the minimum integer that satisfy this equation. This prove that the link schedule for the set of weight obtained from step1 to step3 realizes minimum frame length among link schedules obtained by algorithm 2 with any variations of weights.

Step 4 decides weight values that does not affect the frame length. The objective of step 4 is to increase the value of $\beta(j)$ while the frame length is unchanged. To increase the value of $\beta(j)$ means to decrease the usage of the buffer of communication nodes on average. This is obvious from the meanings of equation2.

If traffic demands are larger than link capacity, there is no set of weights that satisfies equation2, and algorithm 3 does not converge. Let frame length increases by ΔT when $w(j)$ increases by $\Delta w(j)$.

$$\Delta w(j) - \Delta T \frac{\alpha(j)}{c(j)} > 0 \tag{4}$$

If equation4 holds, there is possibility to find the set of weights that satisfies equation2. If equation4 does not holds, step 3 of algorithm 3 stops because the convergence of algorithm 3 is unlikely to happen. Not that equation4 is not a sufficient condition for the convergence of step1 to step3 in algorithm 3, and it is just a empirical guide line to perform algorithm 3.

2.4 Simulation conditions

This subsection explains the conditions of simulations described in the following sections. We use a custom-made simulation program implemented in visual c++ because fast computation is necessary to perform huge numbers repetitive trials. The simulation program simulate a TDMA wireless mesh network.

A wireless mesh network used in the simulations has tow types of communication nodes. One is gateway (GW) which connects to a wired network. The other is mesh router (MR) which connects to other MR or GW by wireless links. Each node is placed to a position so that nodes are uniformly distributed within a given size of square by using uniform random number.

Only up link traffic and down link traffic are considered. For a link l between node a and node b, if node a is closer to a GW, node a is called the upper node of link l, and node b is called the down node of link l. Link l is called a lower link of node a, and the upper link of node b. A node can have multiple lower links and only one upper link. Up link traffic comes from a MR to a GW, and down link traffic comes from a GW to a designated MR. If a GW is not within the range of a MR, intermediate MRs relay the traffic to GW. For up link, data to transmit to a GW is randomly generated at a MR node, and is transmitted through the upper link of the node to the upper node of the link, and then this process continues until the data reaches to a GW. For down link, data to transmit to a destination MR node is generated at a GW and the destination node is decided using random number. The data is transmitted through the lower link of the GW to the lower node of the link, and then this process continues until the data reaches the destination node. The lower link of each node is selected so that the link is on the path form the GW to the destination node. Here the amount of generated data for one unit of time is one unit of traffic demands. For up link traffic, the traffic demands at a node are the summations of the amount of generated data at the node and traffic demands of lower nodes of its lower link. Up link traffic demands is first calculated at a leaf node where only data generated at the node is taken into account. Then proceed to the upper node of its upper link. For down link traffic, the traffic demands at a node is the summations of the amount of data generated at the GW with the node be the destination and traffic demands of the lower nodes of its lower links. It is also assumed that each MR node has a buffer that can store data that can not be transmitted for that period.

Protocol interference model [20] is adopted. Communication range and interference range are concentric circles with the node be the center. The diameter of interference range is longer than that of communication range. Let link l_1 have the upper node a_1 and the lower node b_1, and link l_2 have the upper node a_2 and the lower node b_2. For up link traffic link l_1 interferes with to link l_2 if node a_2 is within the interference range of node b_1, and link l_2 interferes with link l_1 if node a_1 is within the interference range of node b_2. For down link traffic link l_1 interferes with to link l_2 if node b_2 is within the interference range of node a_1, and link l_2 interferes with link l_1 if node b_1 is within the interference range of node a_2. If link l_1 interferes with link l_2 and/or link l_2 interferes with link l_2, link l_1 and link l_2 are considered to interfere each other. For this case we treat node b_1 and node b_2 interfere each other to represent a edge in the corresponding conflict graph where a node corresponding to link l_1 and a node corresponding to link l_2 are connected by a edge indicating the interference between them. More realistic interference model such as signal to noise interference model(SIR model)[20] has been studied [21], and SIR model can be adopted without much difficulty. This is one of future issues.

MRs are associated to a GW so that the MRs can connect to the GW with minimum hops. These association are built by the following steps.

Step1 Associate a MR to the closest GW if the MR is within the communication range of the MR. A MR associated to a GW is called an associated MR and treated to be linked to the GW.

Step2 Establish a link from a MR to an associated MR within its communication range so that the number of hops from the MR to a GW is minimum. The MR is treated to be associated to the GW. Continue this step until no more MRs exists within the communication range of any associated MRs.

As a result, network topology is built. Communication links can also be determined by existing roting protocol as AODV or DSR. Here we assume that the association of MRs to GWs are fixed for simplicity. Then only links associated to the same GW should be the target of link scheduling. In general the association of MRs to GWs and link scheduling should be considered together. Association of a node to a different GW may improve a network performance. This means a different network topology realize better network performance. For this case the optimal link schedule would be obtained by comparing some performance measures by changing MRs association and then by changing link schedule.

We adopt a centralized mechanism for link scheduling where one control node obtain information about the traffic demands at each communication node and which links interfere which links, decides a link schedule for each link, and notify the link schedule to each link. We assume that average traffic demands at each node can be estimated at the time of network setups and the estimation can be modified based on the observation of traffic load at nodes. We also assume that the observation of traffic load can be restricted to some nodes depending on the capability of the hardware of the node or the cost of observation.

Specific numbers for variables in simulations are explained here. The total number of MRs varies from 20 to 80, and the number of GW varies from one to four. The diameter of interference range is 1.3 times longer than that of communication range. For the case the number of communication nodes is 40 and the number of GW is one, the average number of communication nodes located within communication range of a node is 2.3, the average number of communication nodes located within interference range of a node is 3.1, and the average number of hops from a MR to the GW is 3.2. The difference of the number of MRs affects the difference of the number of node within interference ranges. However comparison results shown in the following sections did not show the much difference by the difference of the number of MRs, then they use the results for the case the number of MRs is 40 for the explanation. Initial amount of generated data at each MR node is decided by dividing initial total amount of generated data of a network in proportional to the area of Voronoi cell for the node. Initial total generated data amount of a network is decided so that the average data transfer time is less than a given threshold. Buffer size is 200 times of the unit of traffic demands.

2.5 The evaluation of the proposed link scheduling in adaptability for traffic load change

The link scheduling applying algorithm 3 for periodically updated traffic load is referred to as the adaptive method hereafter, and the link scheduling obtained by applying algorithm 2 for traffic demands at the time before the change is referred to as the fixed method. Comparative evaluations between the adaptive method and the fixed method in terms of average data transfer time and the amount of data to be transmitted have been conducted by using a simulation program. For the evaluation of the adaptivity of the proposed method to traffic demands increase, 20%, 40%, and 60% of MR nodes are selected and their traffic demands are incremented from initial values. Data transmission have been carried out for each incrimination of traffic demands at the selected nodes, and the average data transfer time and the amount of data transmitted of the adaptive method and the fixed method are measured. They are plotted against each incrimination of traffic demands in Fig.1. This is the results for the case the total number of communication nodes is 40 and 20% of the nodes are selected for traffic demands incrimination. The horizontal line of the figure is the rate of data generation increase. It start from 1.0 times of the initial traffic demands, to 1.3 times, 1.6 times, and so on. Average operation was applied for the data transfer time and transmitted data amount from 3000th frame to 8000th frame. The values of first frame to 2999th frame are omitted to avoid the effect of unstable results of the initial phase.

Fig.1 shows that average data transfer time of the adaptive method was kept low until the traffic demands is incremented to 3.1 times larger than initial value. On the other hand, the average data transfer time increased as the traffic demands increased, and the fixed method can not continue transmission due to buffer overflow when the traffic demands incrimination reached to 1.9 times larger than initial value. The adaptive method can continue the transmission until the traffic demands incrimination reached to 4.6 times larger than initial value for up link traffic, and 4.0 times larger than initial value for down link. The amount of data transmitted increases in proportion to the generated data amount until buffer overflow is happened. The results for other network topologies shows the same trend. It is concluded that the proposed method indicate adaptivity for the traffic demands increase.

2.6 The evaluation of traffic load observation restriction on the link scheduling adaptability

2.6.1 Restrictions of traffic load observation

In this section we investigate the impact of the restriction of traffic load observation to limited nodes on the performance of the link schedule built by algorithm 3. We use the following 4 different types of restriction of traffic load observation.

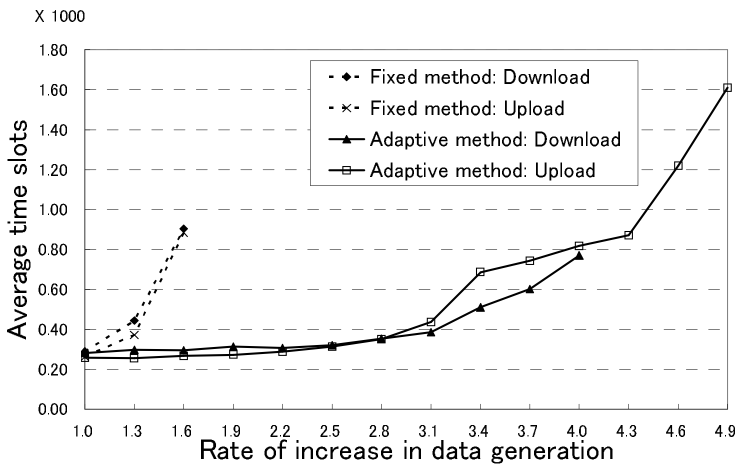
Partial observation 1 Restricted to nodes with high degree

Partial observation 2 Restricted to node with large initial traffic demands

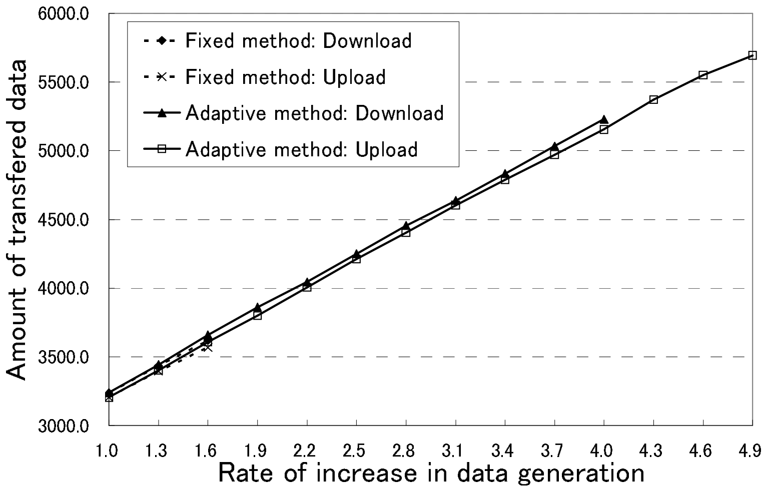
Partial observation 3 Restricted to nodes directly connected to GWs

Partial observation 4 Restricted to nodes with large traffic load at the time of observation

When the percentage of the number of observable nodes is given, nodes with maximum degree are selected and nodes with lesser degree are selected until



(a) Average data transfer time



(b) Amount of data transferred

Figure 1: Comparison between a proposed adaptive method and a fixed method in average data transfer time and amount of transferred data against generated data increase

the percentages of selected nodes reached to the given percentage for partial observation 1. Nodes are selected by the similar way for the other types of observation restrictions. Partial observation 1 is considered to selects nodes that connect many interfering links. Partial observation 2 considers initial traffic demands, but not interference. Links between GWs and nodes selected by partial observation 3 are likely to have large traffic demands and many interfering links because all traffic goes to GWs for up link and comes form GWs for down link. Partial observation 4 selects nodes that have large traffic demands after traffic demands change have happened. This is not feasible restriction because it requires the observation of all nodes to select nodes with large traffic load. Partial observation 4 is taken up just for comparison. We call the link scheduling constructed by algorithm 3 with the traffic load of all nodes observable “full observation method”. We call the link scheduling constructed by algorithm 3 with the partial observation 1 as the restriction of traffic load observation “partial 1 method”. Partial 2 method to partial 4 method were constructed the same way.

For nodes selected to be the target of observation, traffic demands are observed for a give interval of time. Then the weights of upper links of the nodes are recalculated using observed traffic demands. For nodes those are not the target of observation, the weights of their upper links are modified as follows for up link.

Step1 Pick up a node that is the target of observation and the weight of its upper link is changed by the recalculation, then proceed to next step. Stop no more nodes can be picked up.

Step2 Let the node be node a_1, l_1 be the upper link of node a_1, the upper node of link l_1 be node a_2, the upper link of node a_2 be link l_2. The weight of link l_2 is modified so that the weight is minimum integer that is equal to or greater than the summation of weights of lower links of node a_2.

Step3 If the weight of link l_2 is changed, set node a_1 be a_2 and link l_1 be l_2, and repeat step 2. If link l_2 is directly connected to a GW, go to Step1.

The weights are modified as follows for down link.

Step1 Pick up a node that is the target of observation and the weight of its upper link is changed by the recalculation, then proceed to next step. Stop no more nodes can be picked up.

Step2 Let the node be node a_1, l_1 be the upper link of node a_1, the lower links of node a_1 be link $l_2^1, \cdots, l_2^n$. The weight of link $l_2^1, \cdots, l_2^n$ is equally incremented or decremented so that the summation of weights of link $l_2^1, \cdots, l_2^n$ is equal to the weight of link l_1, or minimum integer that is greater than the weight of link l_1.

Step3 If the weight of link l_2^i is changed, set the lower node of link l_2^i be node a_1 and link l_1 be l_2^i, and repeat step 2. If the lower node of link l_2^i is a leaf node, go to Step1.

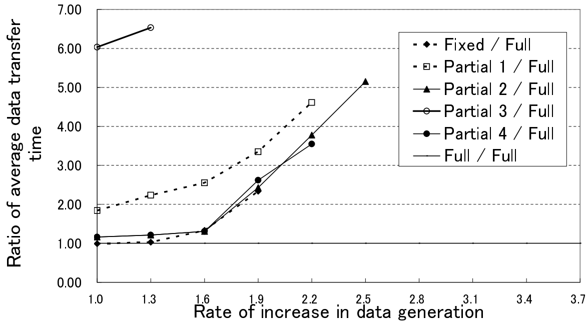
Now weights are modified, and link scheduling with modified weights is updated by algorithm 3.

2.6.2 Comparative evaluation on adaptability among different observation restrictions

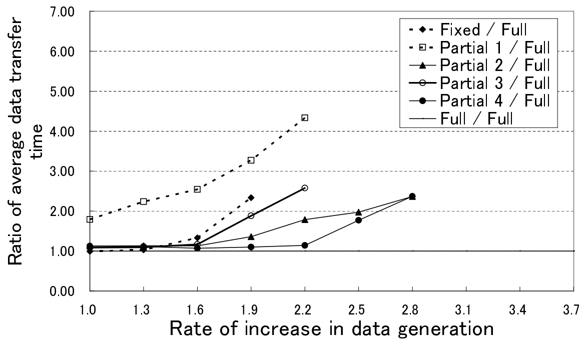
We conducted data transmission simulation. The percentage of nodes that increase data generation at the nodes was switched from 20%, 40%, and to 60% of all nodes. The percentage of nodes those traffic load can be observed was switched form 15%, 25%, 35% of all nodes. The nodes that increase data generation and the nodes traffic load of those can be observed were selected independently by random number. Note that the number of nodes directly connected to a GW may be smaller than the number calculated from the designated percentage for partial 3 method. We carried out this simulation over 100 different topologies. Simulation assumptions are described in subsection 2.4.

To compare the results for different network topologies, average data transfer time is normalized by dividing the average data transfer time of each method by that of full observation method for each topology. Thus the value 1.00 on the vertical axis means the method takes the same time as the full observation method to transfer the same data, and the value 2.00 means the method takes twice longer than the full observation method to transfer same data. The result of down link for a topology with the percentage of nodes that increase data generation 20% is shown at Fig.2. Average data transfer time is not plotted if data transmission is not accomplished because of buffer over flow at given magnitude of data generation increase.

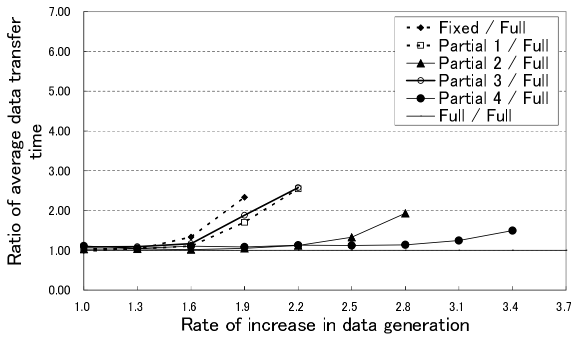
The figure shows that average data transfer time of each method approaches to that of full observation method as the percentage of the number of observable nodes grows. There were no distinguished difference among partial 1 method, partial 2 method, and partial 4 method when the percentage of the number of observable nodes is 15%. Partial 4 method and then partial 2 method show significant superiority over partial 1 method when the percentage of the number of observable nodes grows to become 25% and 35%. The average data transfer time of partial 1 method and partial 3 method are worse than that of the fixed method when the percentage of the number of observable nodes is 15%, and improve drastically when the percentage of the number of observable nodes grows.



(a) Observation coverage = 15%



(b) Observation coverage = 25%



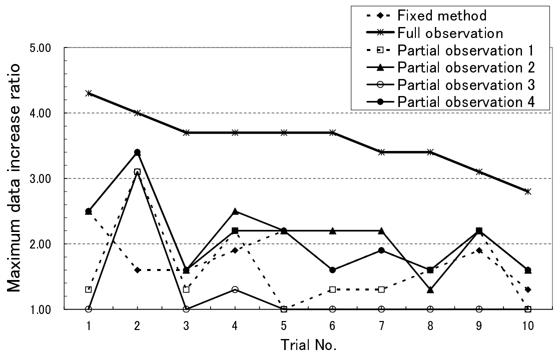
(c) Observation coverage = 35%

Figure 2: Average data transfer time comparison among different partial observation method with the percentage of nodes that increase data generation = 20%

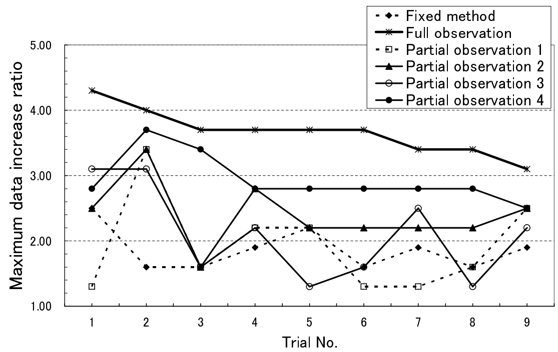
Upper bound of data generation increase where data transmission is successfully accomplished indicates the degree of the adaptability of each method for traffic load increase. To show the dependency on network topologies, the upper bound of data generation increase of each method for 10 topologies with the percentage of nodes that increase data generation 20% are shown in Fig.3. The value on the vertical axis for a method means the magnitude of data generation increment compared to initial data generation that the method can adapt to. The value for the full observation method is considered very close to the network capacity because the link schedule of the full observation method is semi optimal in terms of network throughput.

This figure generally indicates that all partial method improves the data transmission capability as the percentage of the number of observable nodes grows. Partial 4 method and partial 2 method shows a similar properties. Their upper bound when the percentage of the number of observable nodes is 15% for each network topology is almost same with that of the fixed method, and grows gradually for all network topologies as the percentage of the number of observable nodes grows. Especially the upper bound of partial 4 method and partial 2 method approaches to that of full observation method when the percentage of the number of observable nodes increase to 35%. Upper bounds of partial 1 method for some network topologies are very small when the percentage of the number of observable nodes is 15% and 25%, increase significantly when the percentage of the number of observable nodes is 35%. The performance of partial 3 method is generally poor. Its upper bound for some network topologies are smaller than those of the fixed method even when the percentage of the number of observable nodes is 35%. Partial 1 method and partial 3 method are dependent on network topologies. It is considered that there are some nodes that critically affect their performance and the performance greatly depends on whether those critical nodes are the target of observation or not. On the other hand partial 4 method and partial 2 method are such a type of method that receive less effects from specific nodes and can increase the performance if the number of observable nodes increases. This is considered to be good nature because the selection of observable nodes are possible without considering extra conditions. The results for the case that the percentage of nodes that increase data generation is 40% and 60% are shown in Fig.4, and 5 respectively. These figures shows the same trend with that of Fig.3.

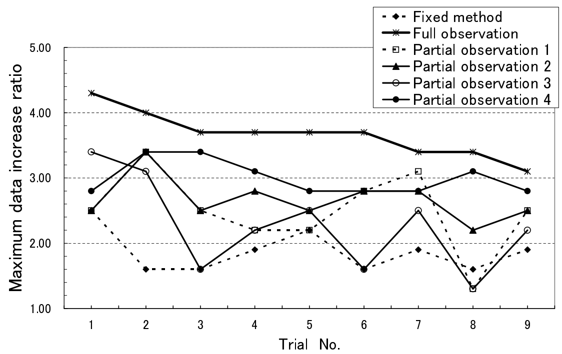
As summary the average of results for all 100 network topologies are shown in Fig.6. Upper bounds of data generation increment for full observation method and all partial methods increase as the percentage of the number of observable nodes grows. When the percentage of nodes that increase data generation grows, the upper bounds decrease for all methods, however the ratio of



(a) Observation coverage = 15%

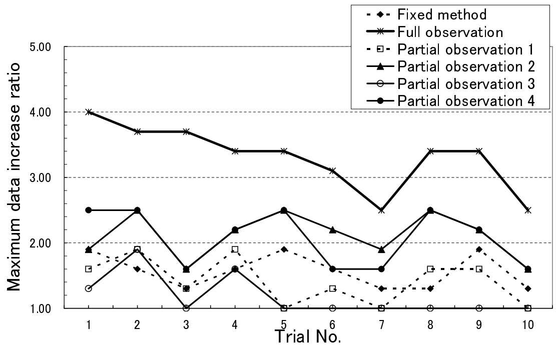


(b) Observation coverage = 25%

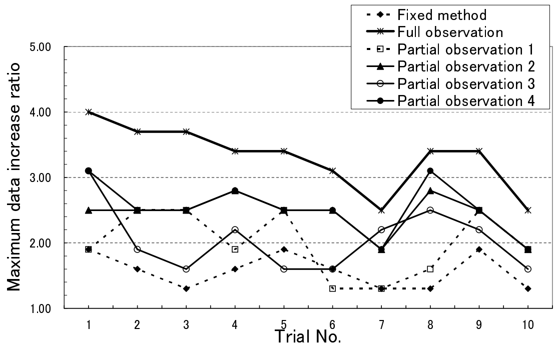


(c) Observation coverage = 35%

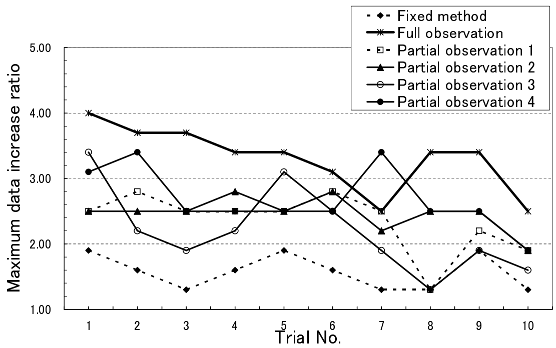
Figure 3: Comparison of upper bound of data generation increase ratio among different partial observation methods with the percentage of nodes that increase data generation = 20%



(a) Observation coverage = 15%

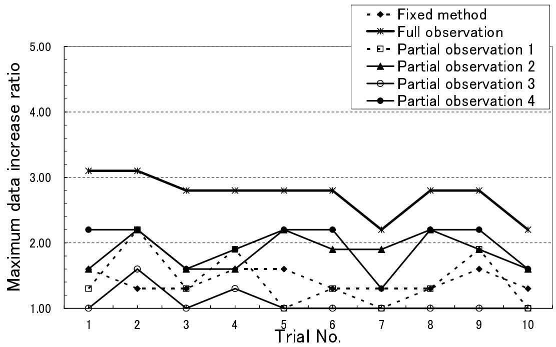


(b) Observation coverage = 25%

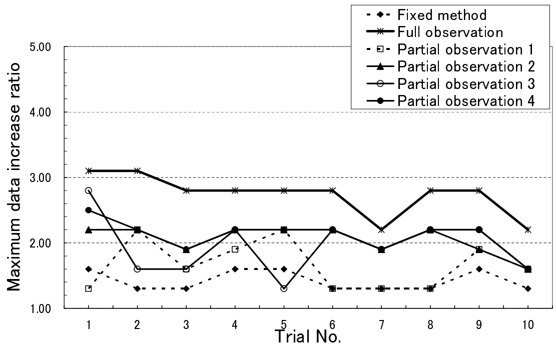


(c) Observation coverage = 35%

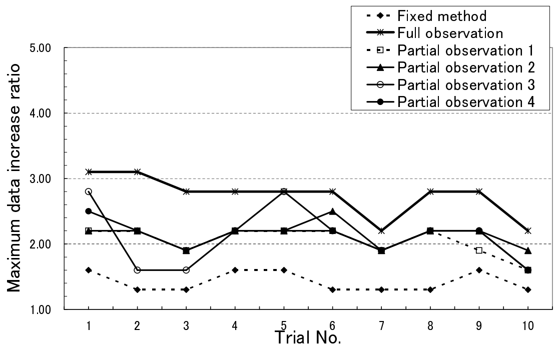
Figure 4: Comparison of upper bound of data generation increase ratio among different partial observation methods with the percentage of nodes that increase data generation = 40%



(a) Observation coverage = 15%

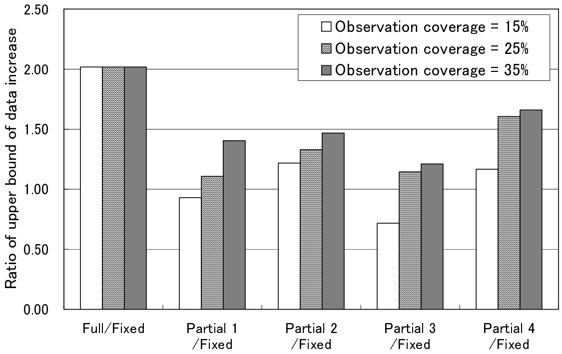


(b) Observation coverage = 25%

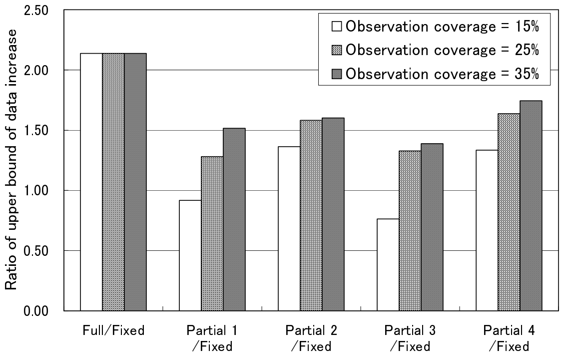


(c) Observation coverage = 35%

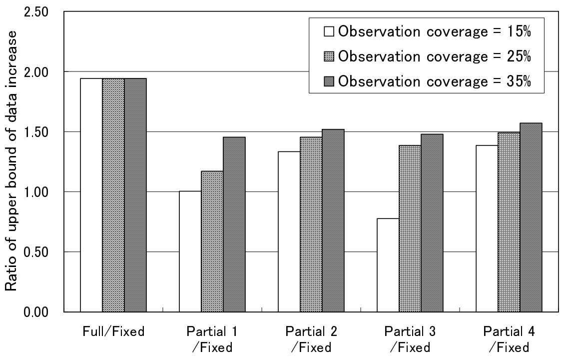
Figure 5: Comparison of upper bound of data generation increase ratio among different partial observation methods with the percentage of nodes that increase data generation = 60%



(a) Observation coverage = 15%



(b) Observation coverage = 25%



(c) Observation coverage = 35%

Figure 6: Comparison of upper bound of data generation of Full observation method and each Partial observation method to Fixed method

upper bound of data generation increment of each method to that of the fixed method were increased. This means algorithm 3 realized the improvement on the data transmission capability against traffic load increase. The improvement for full observation compared with the fixed method is around 200%. The proposed method adapt link schedule after traffic load is observed for s designated time interval, and this means that all traffic is transmitted without modifying link schedule for the time interval even when traffic demands is increased. From that perspective the speed of data generation increment is relatively slow compared to the time interval for weight recalculation in the simulation. It is concluded that the simulation results shows the algorithm 3 can improve adaptability significantly for this speed of traffic load change. All partial methods did not show the adaptability when the percentage of the number of observable nodes is 15%, however as the percentage grows, they showed good performance in the order of partial 4 method, partial 2 method and partial 1 method. When the percentage of the number of observable nodes is 35%, the ratio of upper bound of data generation increment of each method to that of the fixed method becomes from 121% to 174%. The change of the percentage of nodes that increase data generation did not affect the trend, and partial 4 and partial 2 method showed the superiority for all the percentage of the number of nodes that increase data generation. However, the difference among partial methods becomes smaller as the percentage grows.

The superiority of partial 4 method indicates that the traffic load observation at the nodes those traffic load are large is effective for algorithm 3 to handle with traffic load increase. Partial 2 method is the second best. Partial 1 method and partial 3 method were supposed to be effective because they observe nodes which connect heavy interfering links. However the simulation results indicate that observing nodes with large traffic is much more effective than observing nodes with complex structure in terms of network topology. This is regarded as a reason for the network topology dependence of the performance of partial 3 method and partial 1 method because they restrict the observation to nodes with complex topology structures. The partial 2 method is feasible to implement and its performance is relatively impervious to the difference of network topology. In real situation network capacity is large enough for single source of data generation, and the behavior of network is effectively controlled by statistical handling. Thus traffic load change will be likely to happen gradually if statistical there is no special event happened. Thus it is concluded that nodes those are assumed to have large traffic demands at the time of network implementation should be selected for the target of traffic demands observation if the restriction on the number of observable nodes are imposed for a network.

2.7 Summary

As a first step to build a control method for wireless networks adaptive to changes in conditions for varieties of environments, we put emphasis on the effect of traffic load change for the exploration of the effect on the network performance. We then investigated the effect of the restriction of traffic load observation on the network performance . We proposed a method to design a link scheduling of a mesh network that adapts the change of average traffic load of communication links. This method is based on the weighted graph coloring and we came up with new weight updating for given traffic load. We conducted a simulation where the amount of data generated for a part of communication nodes increase and upper bound of the amount of data generation where all generated data were successfully transmitted to designations were investigated as a indicator of the throughput of the network. When the percentage of nodes that increase data generation grows, the upper bounds decrease for the proposed method, however the ratio of upper bound of data generation increase of the proposed to that of the fixed method were increased to 200%. This means the proposed method can realize the improvement on the data transmission capability to handle with traffic load increase. The speed of data generation increase is relatively slow in the simulation. The simulation results shows the proposed method can improve adaptability for this speed of traffic load change. We also investigated the effect of the restriction of traffic load observation to limited nodes. We evaluated the upper bound of networks designed by the proposed method with traffic load observation restriction. All restricted networks did not show the adaptability when the percentage of the number of observable nodes is 15%, however as the percentage grows, they showed good performance in comparison to non-adaptive method. When the percentage of the number of observable nodes is 35%, the ratio of upper bound of data generation increase of each method to that of the fixed method becomes values from 121% to 174%. Among the restrictions, restriction to node with large amount of generated data at initial time showed the superiority for all the percentage of the number of nodes that increase data generation. The change of the percentage of nodes that increase data generation did not affect the trend. This means even if the locations of nodes that increase the data generation are biased, this is corresponding to the case the percentage of node that increase data generation is low, the proposed method can adapt to traffic changes. The difference of network topology also did not affect the results of the method, while observation restriction to nodes connected to GW and nodes with large degree received the effect of the network topology. As a conclusion, observation restriction to nodes that is likely to have large traffic load should be adopted for the design of network if restriction on the number of observable nodes are imposed for the network.

3 Control method for application selection adaptive to user activities

3.1 Modeling of user activities

Context-aware computing has been a popular research area, and many context-aware services have been proposed and demonstrated. Although they are designed to assist users in the real world, they support only a limited number of user activities. A location-based restaurant guide, for example, is useful for obtaining a list of restaurants near the user's current location. While it may adjust the listing based on the user's food preferences and previous dining experiences, the user must still choose an appropriate restaurant from the list by taking into account factors not directly related to dining. For example, if the user's purpose in visiting a restaurant is to meet colleagues, then restaurants suitable for a business meeting are more appropriate. Moreover, if the colleagues are on their way to the airport, the top priority may be the ability to arrange for a taxicab to take the colleagues from the restaurant to the airport after the meeting. In short, location-context assistance can support a user's activities to only a certain extent. A function must be added to the restaurant guide that can understand a wide variety of user activities as well as the dependency between the requirements for an appropriate restaurant and user activities before, during, and after dining. Simply enhancing context-awareness by using additional context will not provide these capabilities. Thus the applicable domain of a context-aware system can be very limited without the understanding of user activities. In addition to these drawbacks, conventional context-aware system that was designed to fit with a specific state of condition can not follow the change of condition state.

In order to overcome these difficulties, it is necessary to construct the deep understanding of a wide varieties of application related conditions and find a way to associate each state of the conditions to appropriate application parameters to adapt to the conditions and to follow the change of those condition state. Among application related conditions selected are user activities for the primal target of our research. This is because most of applications are designed to provide functions and information to users and thus their behavior are expected to meet user's needs. Issues for building control methods of the behavior of application adaptive to user activities are the construction of the deep understanding of a wide varieties of user activities and the development of a way to control application behavior by the state of user activities.

From the view point of applications designed to work for users, user activities can be understood as solving problems to satisfy user's needs and to realize user's wants. To solve a difficult problem, it is common manner to divide the problem to smaller problems that are easier to handle with. Likewise a more general user activity corresponding to solving a large problem is decomposed into a more concrete user activities corresponding solving smaller problems decomposed from the large problems. It is very important observation that there are different generality levels among concepts of user activities. This means some activity concepts are considered to be parts of other concepts. This observation lead us to construct hierarchical structure of concepts of user activities. We call this user activity model, and our It is very important observation that there are different generality levels among concepts of user activities. This means some activity concepts are considered to be parts of other concepts. This observation lead us to construct hierarchical structure of concepts of user activities. We call this user activity model, and our control method use this user activity model to handle a wide varieties of user activities and changes of user activities.

The difficulties to build such a user activity model is comprehensiveness of its coverage and consistency with in the model. Most of previous research on the construction of user activity model are sensor centric. This means that their model represent human behavior in terms of captured sensing data. Because the expressiveness of sensing data is usually limited, their models represent only limited aspect of user activity. [49] built a psychological human behavior model. The model represents some limited properties of human behavior that can be observed by questionnaires. The model of [50] is based on images captured by wearable cameras. Car driving skill is modeled as part of human behavior models by using sensor [51] and 3 dimensional simulator [52]. [53] took into account not only data sensing the appearance of activity itself but also data sensing factors causing the activity, however, the coverage of the user model are bounded. It is concluded that sensor centric approach does not meet the requirements of the understanding of a wide varieties of user activities.

Comprehensive semantic level model of user activities are necessary to meet the requirements and related previous research are found in the area of knowledge representation (KR) [47]. KR research involves analysis of the way to use a set of symbols to represent a set of facts within a knowledge domain and the way to accurately and effectively reason. A symbol vocabulary and a system of logic are combined to enable inferences about elements in the KR to create new KR sentences. Logic is used to supply formal semantics of how reasoning functions should be applied to the symbols in the KR system. Logic is also used to define how operators can process and reshape the knowledge. A key parameter in the construction of a KR is its expressivity. If a KR is more expressive, it is easier and more compact to express a fact or element of knowledge within the semantics of that KR. However, more expressive representations are likely to require more complex logic and algorithms to construct equivalent inferences. A highly expressive KR is also less likely to be complete and consistent. Less expressive KRs may be both complete and consistent.

In computer science, particularly artificial intelligence, a number of representations have been devised to structure information. KR is most commonly used to refer to representations intended for processing by computers. Representing knowledge in such explicit form enables computers to draw conclusions from knowledge already stored. Major projects attempted to encode wide bodies of general knowledge. Through such work, the difficulty of KR came to be perceived. Then a number of ontology have been developed. In computer science and information science, an ontology is a formal representation of knowledge as a set of concepts within a domain, and the relationships between those concepts. It is used to reason about the entities within that domain, and may be used to describe the domain. An ontology provides a shared vocabulary, which can be used to model a domain — that is, the type of objects and/or concepts that exist, and their properties and relations. If we have a good ontology for some domain, we can build the representation of knowledge of that domain comprehensively and consistently by using vocabulary provided from the ontology. There is a long history of work attempting to build good ontology for a variety of vdomains. One example is the Dublin Core. The Dublin Core is the set of vocabulary to represent meta-data. It provides a small and fundamental group of text elements through which most resources can be described and cataloged. Using only 15 base text fields, a Dublin Core meta-data record can describe physical resources such as books, digital materials such as video, sound, image, or text files, and composite media like web pages. Meta-data records based on Dublin Core are intended to be used for cross-domain information resource description and have become standard in the fields of library science and computer science. Implementations of Dublin Core typically make use of XML and are Resource Description Framework based. Dublin Core is defined by ISO through ISO Standard 15836, and NISO Standard Z39.85-2007.

Although there are many domain ontology constructed, they are the results of huge efforts, and it is not easy to construct ontology that covers wide domains. On the other hands, there are research activities to construct ontology of task, not domain [42],[43], [44],[45],[46]. Task concepts are relatively independent from domain and thus can be reused for different domains. If we can restrict the target of ontology for user's tasks that can be solved by computer applications, it is feasible to build good ontology that covers those user's task. Then semantically appropriate applications can be selected for given user's task based on them.

We built our control method using a user activity model based on the research of task ontology mentioned above. Our user activity model has sufficient expressiveness to support a wide variety of application related user activities. In the model a user activity is represented as the performance of a series of tasks for solving a problem that a user or a system encounters. Because the generic user activity model is based on well organized generic task ontology, an instance level user activity model for a specific domain can be easily and effectively constructed from them. Here the associations of applications to appropriate user tasks are constructed. Applications are considered to be a method to accomplish the corresponding user task. The control of application selection is realized by selecting user task in the associations. Thus the control method is to select appropriate task from the collection of the associations between user tasks and applications from detected user activity or user input, and the feature of the way to construct the control methods is that it can create huge numbers of associations at relatively low cost and with very few contradictions.

3.2 Motivation scenario

In this section, we use the following scenario to further illustrate requirements for user activity model necessary for future context-aware applications.

Ms. A was at home in the morning. She started a home monitoring application, which would record her physical activity context at home through the day and also give her alert if pre-registered events are detected within the house. She carries an RFID tag. Dishes, pans and other kitchen ware are attached by motion detection sensors, touch detection sensors and other sensors. Cameras are equipped at around the kitchen and a living room. TV sets, hard disk recorder, cell phone and other mobile communication devices are connected to each other through indoor wireless network and to the Internet through WAN. When she is using a hard disk recorder and a mobile communication device, for example, huge data such as high definition video streaming data is transmitted over the indoor wireless network, and when she is out of home, only relatively small amount of surveillance data is transmitted over the network. While she was preparing breakfast for her and her dog, she found a attractive dish in a cooking program in TV. She launched TV related information portal application on a mobile device, and found the dish was mentioned favorably by many people in SNS services. She selected the recipe for the dish, and the application collect information regarding kitchen equipment and foodstuff available there at that moment,and modify the recipe so that she can cook the recipe without getting additional stuff not available there at this moment. A cooking assist application showed her cooking instructions step-by-step according to the modified recipe on a near-by screen. She can interact with the application by touching or moving appropriate kitchen ware. She may request a detailed instruction of making soup by shaking a soup pan while general making soup instruction is displayed on the screen. She can skip to the next instruction by tapping the pan. On the other hand, if her body is too close to a pan with boiling water, the home monitoring application flashes an alert light at the kitchen. When she goes to a family room to feed her dog with dog food, the cooking assist application is automatically suspended. If the movement of some dish is detected while she is in the family room, the home monitoring application send an alert message and visual information captured by the cameras in the kitchen to a screen close to her in the family room. When she goes back to the kitchen, the cooking assist application is resumed. In addition she is always using a daily chores reminder application that reminds her what she registered as what she should do. Just after she wakes up, the application tells her to take a medicine. When she is about to leave home, the application continues to tell her to lock the unlocked windows until all windows are locked. It also suggests her to bring an umbrella according to a weather forecast. Today while she was cooking, she thought she would cook the original recipe by obtaining some foodstuff necessary for the original recipe. She registered it to the daily chores reminder application. The reminder application launched an application composition service that search necessary applications in the Internet taking her context into account and compose them to accomplish the chore registered at first time. In this case her schedule and daily activity area information were considered and the selected supermarket that sell the foodstuff was located close to her commuting route. Then the application will remind her every time she is close to the supermarket until she get it. When she is out of her home, the home monitoring application automatically changes its behavior and notifies her at her cellular phone only when the dog goes out of the house and people without authorized identities try to enter her house.

We make three observations in this scenario.

- User activities are affected by people and pets around the user. Some activities are for herself, some activities are for others. Some activities are conducted by group of people, and some activities are carried out by others for the user. .

- Different context requires different method to solve problems. For example, her problem is to obtain foodstuff required for the original recipe, and if her location is close to a store selling the foodstuff, she would use a method of going to the store and buy it. If her location is far from the store, she would use a method of purchasing the foodstuff on a web site where she can buy it.

- Among context-aware applications triggered if pre-registered multiple contexts are detected, some applications require ordered sequence of context detection, other do not. The cooking assist application required the appropriate context to be detected in the pre-defined order. The daily chores reminder application did not care which unlocked window was locked first.

These observations lead to the understanding of the features of application that user activity model have to be able to handle with.

3.3 User activity model based on task ontology

3.3.1 Construction of user activity model

We treats a user activity as the performance of tasks necessary for solving a problem that the user encounters. Therefore we adopted an approach to represent user activities from view points of user's task. Although there are huge numbers of tasks, the target of model to be constructed can be limited to the scene that computer applications can supports. Organizing task concepts is considered to be easier than that of domain concepts, because task is relatively independent of domain. It is also said that task is able to be decomposed into more basic tasks which have a generality in the abstract space. For example, a task concept "buy a ticket for a movie" consists of two task concepts, "buy something" and "receive service". Both concepts can be applied to modeling similar tasks in different domains. Task concept thus has a generality in its nature and hence if basic task concepts are built, complex task concepts are constructed by combining such basic task concepts. This will help the construction of user activity model based on task concepts.

For better design, vocabulary for the model should be carefully defined and systematized. Ontology for the user task should satisfy the requirement. Thus, user activity model was generalized and organized using vocabulary of the task ontology [42],[43],[44],[45],[46]. Entities of task ontology are task concept and method. We assume that the world can be described as the state of situation. An action change the state of the situation into different state. Task concept describes the target of an action, which can be re-stated as the target state of situation that the action realize. How to do the action is called method. Fig.7 shows the task concept of "buy". A concept is described by hierarchically structured properties that constitute the concept. For concept "buy", primal

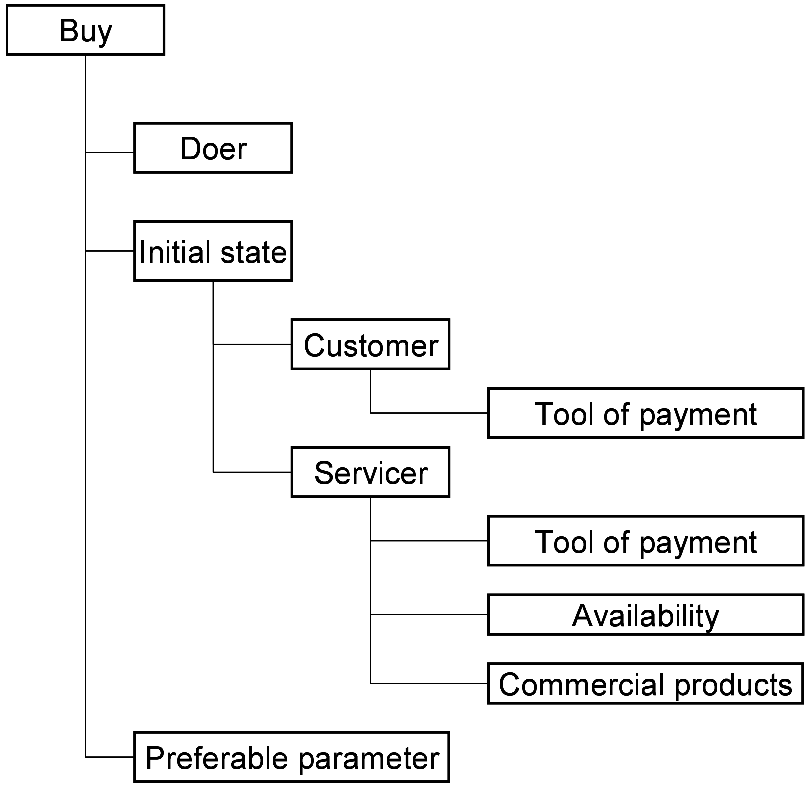


Figure 7: Task concept entity of "buy"

properties are doer that is human who buy, initial state, and preferable parameter. Initial state is further described by properties of customer and servicer. Then servicer is further described by properties of payment tool, availability of service, and commercial good that is the target of "buy". There are a couple of ways to buy. These are represented by "method to buy" shown in Fig.8. Ways to buy represented in the method are "teleshopping", "buy at a shop", "buy through the Internet" that are connected to "method to by" by is-a relations. The method of payments "Buy on a charge account" and "Buy by cash" are also connected through is-a relation to "method to buy".

As mentioned above we treats a user activity as the performance of tasks necessary for solving a problem that the user encounters. A general approach to solving a large and/or abstract problem is to divide it into smaller specific sub-problems. It has been shown that daily human life is driven by "proximal goals" (short-term goals), which are derived from "distal goals" (long-term goals) [25]. Our idea is to decompose the user's task of solving a problem,

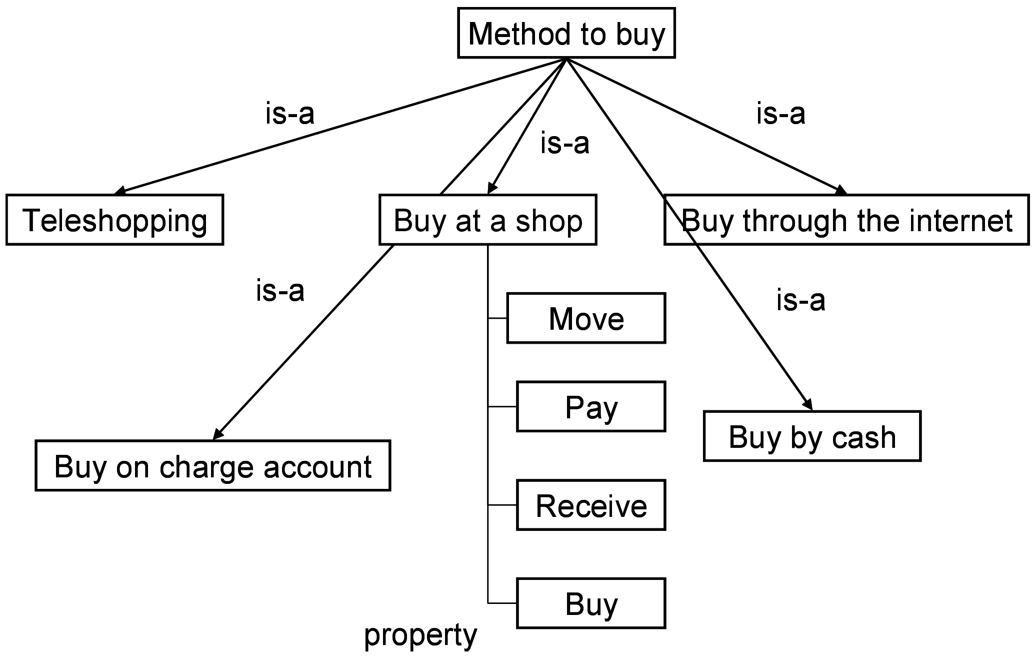


Figure 8: Method entity of “method to buy”

which corresponds to reaching a “distal goal”, into sub-tasks of solving sub-problems, which corresponds to reaching “proximal goals”. In our user activity model, the representation of a task of solving a large problem are decomposed into the representations of sub-tasks of solving the sub-problems decomposed from the large problem. Task itself is represented by task concept and its method using vocabulary of the task ontology.

Service providers usually have implicit business models about their own services, however, they do not have generic models to represent user's general activities. This is one of the reason why the construction of comprehensive user activity model is difficult. It is easy to construct small size of model. However, it becomes extremely difficult if the size of the model becomes large. Coverage of such model tends to be poor, and it is likely to include contradiction within the model. Generic models which are designed by experts will help the construction of user model with relatively large size.

Our approach based on the task ontology enables us to describe user activity models in terms of generic task vocabulary. This is why we can construct huge numbers of activity descriptions at relatively low cost and with very few contradictions. In addition, activity representations based on generic task vocabulary can be reused to describe similar activities because generic task vocabulary are detached from domain model. A model of the task "move", for example, can be applied to model other movement tasks like travel, commute, and so on. This will improve the efficiency of user activity model construction.

3.3.2 Generic user activity model

As described in previous subsection, we describe a user activity as a task of solving a problem and that is described as the combination of "the result of solving the problem" and "the method of solving the problem". We call "the result of solving the problem" the task concept and it is the purpose for which the task is accomplished. "The method of solving the problem" is called the method of achieving the task. In this manner a task is represented by a task concept node and method nodes. Since there can be different methods to achieve the same result, task itself is described by the hierarchical structures of task concept nodes and method nodes.

Description of our user activity model starts from the task at the level of large granularity. Next, methods to achieve the task are linked, and each of the methods is decomposed into a sequence of sub-tasks. This process continues until the granularity of task concepts reaches the granularity of available applications. The "method" in the user activity model is similar to "method" of CommonKADS [26] and "how to bundle" of the Business Process Handbook [27]. Following this process, task of the large granularity is decomposed into sub-tasks via methods. Fig.9 shows the user activity model of "Move to an amusement park". Task "Move to an amusement park" is achieved by the method "Move by a car". The method is composed by a sequence of task concepts. Among them task "Prepare for a car" is achieved by one of two methods, one is "Use a rental car", and the other is "Use user's own car". Those methods are decomposed to appropriate sub-task concepts.

An important feature of the user activity model is that it includes prevention tasks that prevent obstacles from happening, and solution tasks to solve the problems which have happened. For example, the task "Drive a car" has two kinds of obstacles: "Trouble of the car", and "Traffic jam". Then prevention/solution tasks are described and linked to the obstacles. "Drive a care" task may be obstructed by "Traffic Jam", and we can prevent the occurrence of the obstacle by the task "Traffic jam forecast", for example. Those obstacles and solution tasks are linked by "prevention" links. On the other hand, we can solve the obstacle "Trouble of the car" by the task "Repair" when the trouble actually occurred. Those solution tasks are linked to the obstacles with a "recovery"link. After the step of modeling the prevention/solution tasks, goes to the step to description of methods to achieve the tasks. The prevention task,

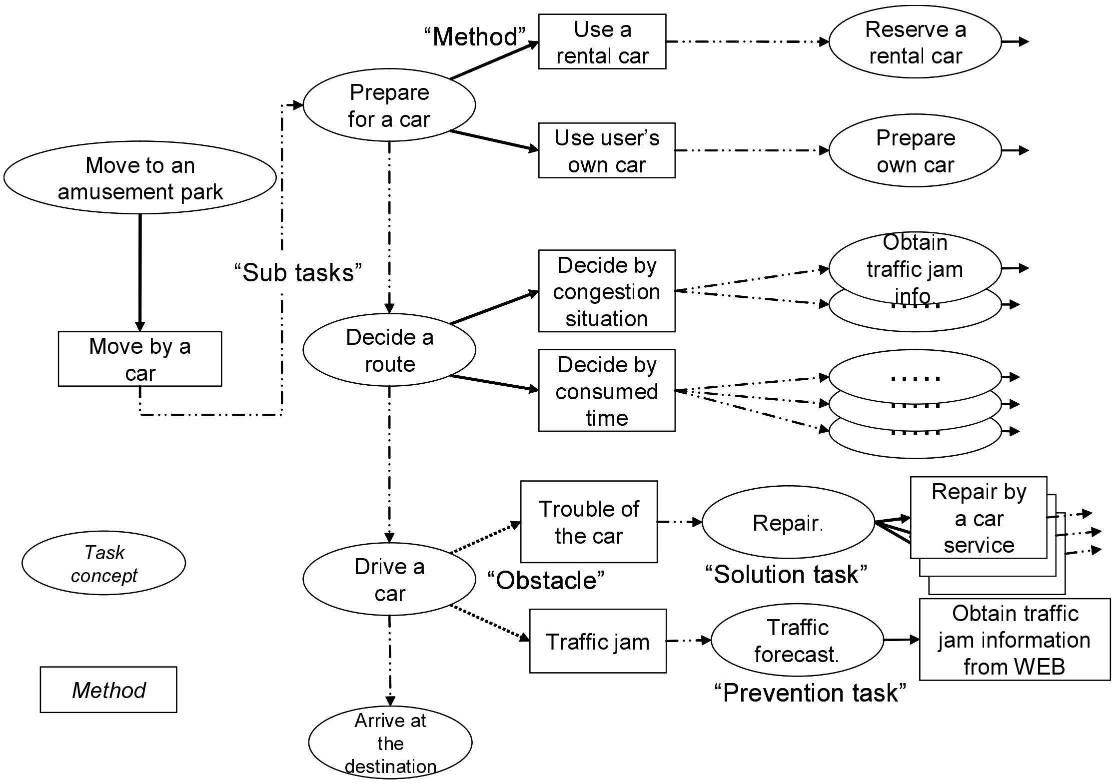


Figure 9: Sample of generic user activity model for "move to an amusement park"

"Repair", can be achieved by a method "Repair by a car service". One of valid use case for the application selection is to provide methods to prevent/solve problems for the users. Applications are considered as methods for appropriate task concepts. This consideration is used in the association of task concept and applications implemented in an instance activity model explained in the following subsections.

3.3.3 Domain dependent user activity model

Domain knowledge is introduced here to associate domain dependent tasks to a generic task concepts. Domain knowledge covers mainly object concepts and those can be are objects of task. Now domain dependent tasks are generated by adding object concept to generic task concept. For example, a domain specific task concept "buy clothes" is generated from a generic task concept "buy" and a domain concept "clothes".

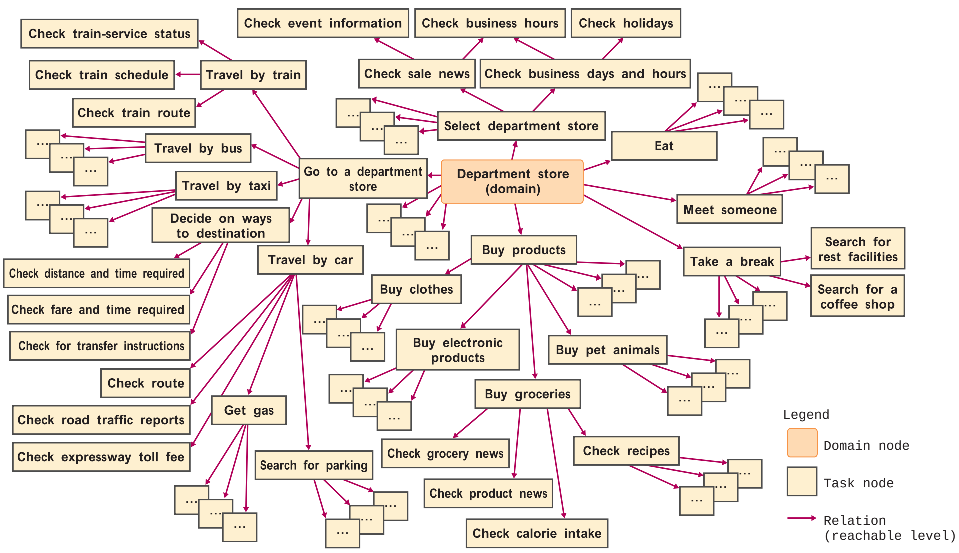


Figure 10: Domain dependent model for user activities related to department stores

Fig.10 shows the user activity model for the domain of department stores. The model is constructed from the generic model of user activity in a facility by adding objects relevant to department stores including clothes, parking, grocery, and electronic products.

3.3.4 Instance level user activity model

Finally the user activity model is instantiated. Instantiation means the construction of user activity model for a specific situation. For example, a user activity model for a department store is instantiated to a user activity model for department store A. Objects in the model correspond to object instance at the department store, and methods in the model correspond to methods available at the department store. Now an application is associated with an appropriate task concept node in the instance model. Applications are considered methods to accomplish corresponding task concepts. It becomes possible to use sensor data to detect instance level of user activity. For example, a task “Enter the entrance of department store A” can be detected by human detective sensor around the entrance. Our user activity models consists of generic user activity model and instance level user activity models, and this enables both the wide coverage of user activity representations and sensor triggered semi-automated processing at the same time. This is the original feature of our user activity

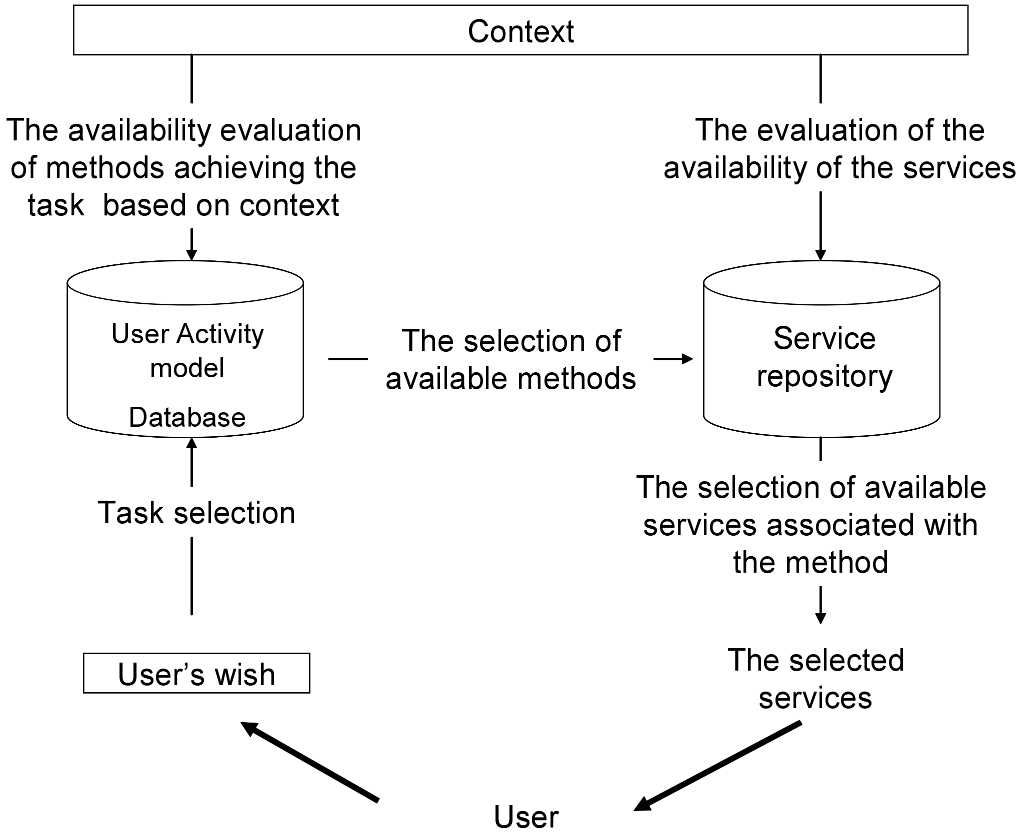


Figure 11: User activity model based service selection schema

model. Next issue is building control mechanism based on this user activity model.

3.4 User activity-aware service selection schema based on activity model

A high-level illustration of the proposed user activity model based service selection schema is shown in Fig.11. The user activity model data is stored in a user activity model database. Service IDs, such as the uniform resource indicator (URI) of services, and information regarding their associations with the task concept nodes in the activity model are stored in a service repository. Users make a request to find appropriate services by, for example, inputting keywords indicating activities that they wish to perform. The user's wishes are compared with the descriptions of task concept nodes in the user activity model, and the node with the most closely matching description is selected. If the selected task concept node is too general, the user may be asked to choose from among the sub-task task concept nodes linked to the selected task concept node. The contexts of the user and environment are also considered when evaluating the availabilities of the different possible ways of performing the tasks represented by the method nodes. Only those method nodes judged to be available based on the context information are followed when traversing the links from the selected task concept node. If a method node associated with services is reached, the association links are followed, and appropriate services are found. Context information is also used to evaluate the availability of services in a given situation, and the services judged to be available are presented to the user. If the context information shows, for example, that the request was made during the day, when train services are fully available, "taking a train" is usually appropriate. However, if it was made late at night, "taking a taxi" or "driving a car" might be more appropriate. Some services may be available only in a limited area, such as within a shopping mall, so user location is important in judging service availability. More sophisticated interpretations of context would be particularly helpful for service selection in some cases. If a user is in a meeting room discussing the stock market with some colleagues, services appropriate for a business meeting situation should be selected. If the user remains in the same room after the meeting, chatting with colleagues about last night's big game, services appropriate for leisure time would be acceptable. There has been some work on building ontology that describe such complicated situations [28]. We plan to enhance our service selection schema by using those situation ontology.

3.5 The development of a user activity-aware information delivery system

3.5.1 A prototype of information delivery system

We built a prototype of a user activity-aware information delivery system for a indoor consumer store. The overall system configuration is depicted by Fig.12. The location of a mobile phone is obtained by using RFID. The location information is sent to a navigation server and the sequence of captured locations is interpreted by the behavior estimation module as a user activity. Appropriate navigation information is selected by the navigation information selection module and the navigation information delivery module sends the selected navigation information to the mobile phone of the user.

We used RFID for positioning of a user. A user is supposed to carry a mobile

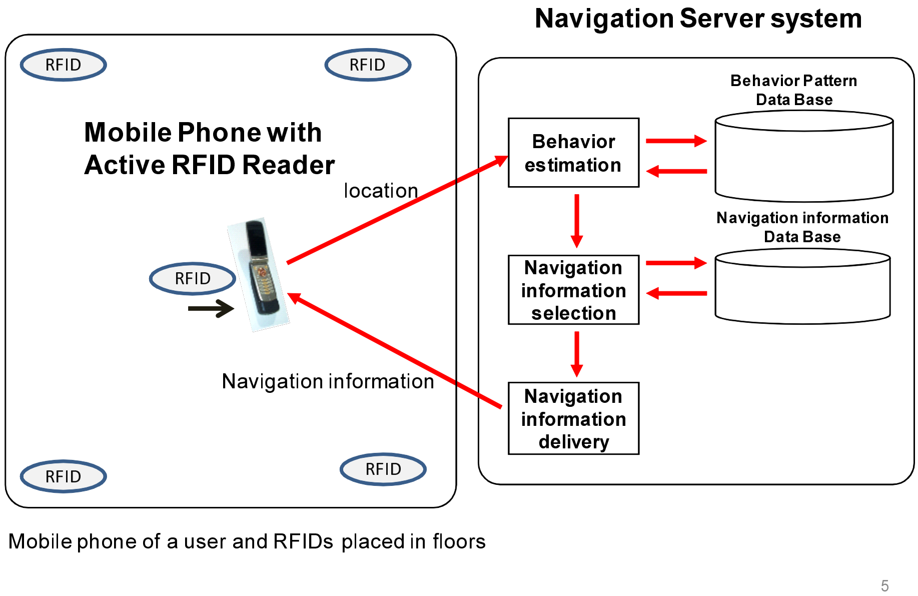


Figure 12: Configuration of the prototype system

phone with active RFID reader and RFIDs are set in environment. RFID send back its identification as a response for a signal emitted from an active RFID reader. The active RFID reader selects the closest RFID by comparing the time to receive response because the closest RFID return a response with shortest time. The active RFID reader reads the ID of the RFID closest to the mobile phone. The mobile phone sends the ID to behavior estimation server where ID is transformed to location, and the sequence of captured locations of the mobile phone is interpreted as a user activity by comparing user model in the behavior estimation module. This interpretation is conducted by matching the sequence of captured locations with a sequence of tasks in the user activity model in the behavior estimation module. Once user activity is matched, appropriate navigation information is decided from the lists of delivery messages based on the associations of tasks to navigation messages. Finally the information is sent to the mobile phone of the user and displayed on the screen of the phone. User sometimes would be navigated to a store appropriate for the user or sometimes recommended to participate in events. It is decided by previous user activities recorded in the sequence of captured locations.

3.5.2 A trail in a real commercial facility

We provided a trail service at a department store in Yokohama, Japan for 2 weeks from 16th of September, 2006. The service was available every floor of the department store that has 10 floors above ground and 2 basement floors. The total number of RFID deployed in the department store is 150, and this means 10 to 12 RFIDs per a floor were set in average. The model of consumers activities used for the trial was constructed using the domain dependent generic user activity model shown in Fig.10. The number of the sequence of activity representations borrowed from the generic model are around 300. The model of instance activities were then constructed by instantiating the generic model to each floor, each store, each store group, and each message. The department store has 12 floors and there are about 50 stores on each floor. Messages were updated every week. Thus the size of instance activity representations in the model is around 3000. And rules to decide appropriate message from selected instance activity are around 8000. The messages include the following types of information.

1. Introduction of each store and floor. It include the location information and items sold there. Introduction of utility facilities such as resting space and storage facilities is included.

2. Announcement of event that would be provided in the department store.

3. Announcement of items for sale, especially items newly arrived. This includes food available at limited time.

The part of the task model for this prototype is shown in Fig.13. The figure shows the association of tasks to delivery information. For example a delivery information regarding newly arrived items for sale at a shop is associated to a instance user activity of arriving at the shop. The information is sent to the user who is detected to arrive at the shop.

646 people participated in the trial. 86% of the participants is female and 60% of the participants is forty's or over. Most of the participants are house wives. They rent the mobile phone with an active RFID reader and carried it while they were shopping and eating in the department store. The system delivers navigation information to the user according the trace of the location of the user, and they were navigated by the information to shops in the department store.

The summary of the evaluation of the trial participants is showed in Fig.14. 55 people out of 646 participants were satisfied very much with this trail service. 225 people were satisfied and 229 people were satisfied some time. 194

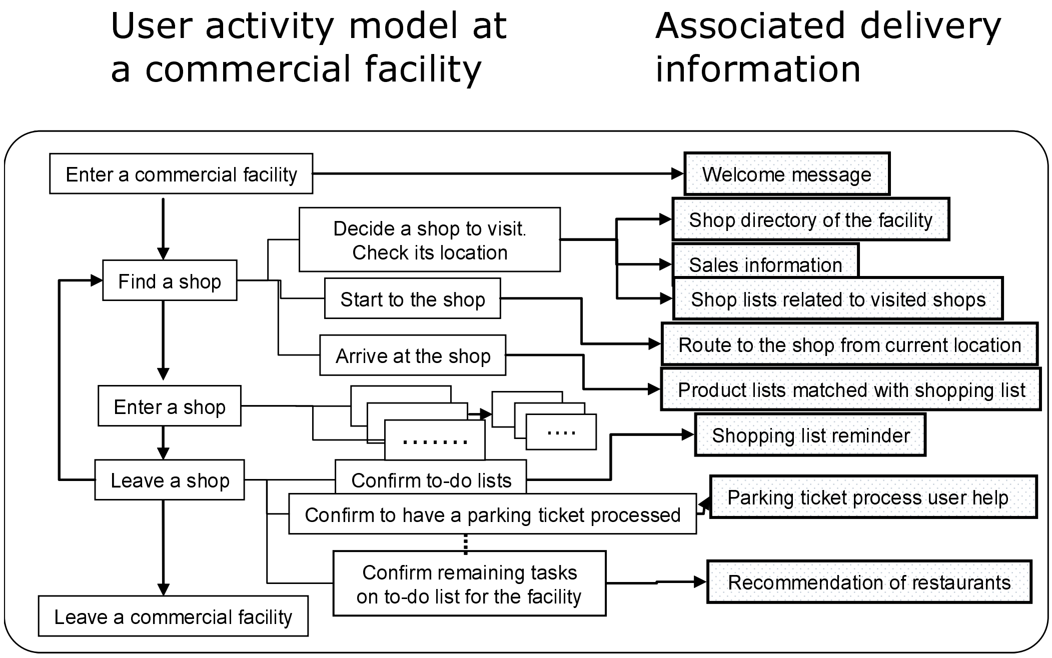


Figure 13: User activity model in a commercial facility and associated delivery information

people found appropriate shops and products by the information sent from the system, that were not noticed without this system. The successful acceptance of the trial proved the construction of huge numbers of delivery information list associated to user activity model were valid and effective.

Analysis of movement sequence of participants developed new knowledge regarding user activity in the department store. Some of the knowledge are

- Visible escalators are keys for consumer navigation.
- Age property of consumers works for the segmentation of shop category.
- Time dependent event was attractive for consumers of all ages.

These results are important and useful for marketing and store placement design for the department store.

3.6 Summary

The semantic model to describe user activities has been studied and constructed. We treats a user activity as the performance of tasks necessary for

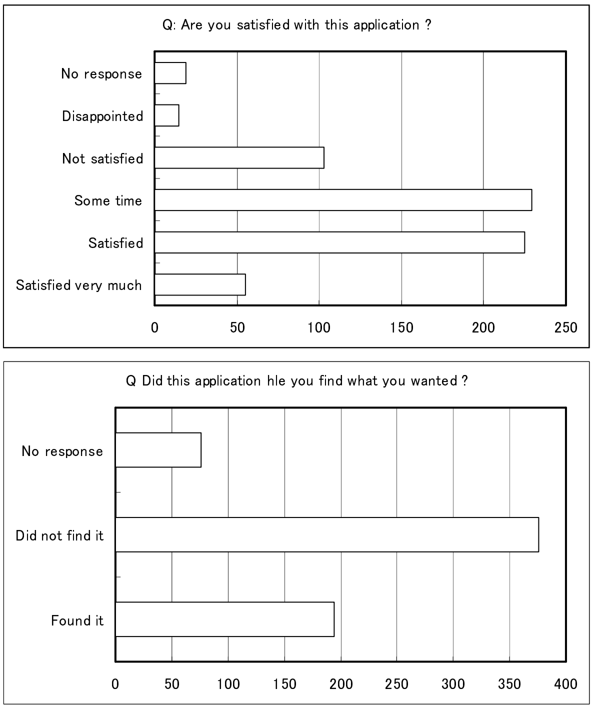


Figure 14: Evaluation results by participants for the trial

solving a problem that the user encounters. The representation of a task of solving a large problem are decomposed into the representations of sub-tasks of solving the sub-problems decomposed from the large problem. Task itself is represented by task concept and its method using vocabulary of task ontology. Description of user activity model starts from the task at the level of large granularity. Next, methods to achieve the task are linked, and each of the methods is decomposed into a sequence of sub-tasks. This process continues until the granularity of task concepts reaches the granularity of available applications. The user activity model also features that it includes prevention tasks that prevent obstacles from happening, and solution tasks to solve the problems which have happened. We constructed generic user activity model that contains hundreds of general task concepts. We build instance level user activity model for a specific facility from the generic user activity model. This leverage the generic user activity model so that we can populate several thousand specific model relatively low cost with very few contradiction. An application is associated with an appropriate task concept in the instance model. Applications are considered methods to accomplish associated task concepts. It also becomes possible to use sensor data to detect some of instance level user activity. In this manner, our user activity model consists of generic user activity model and instance level activity models, and this enables both the wide coverage of user activity representations and sensor triggered semi-automated processing at the same time. This is the original feature of our user activity model. Based on the user activity model we built application selection schema. A given target task is matched to the task concept in the user activity model, the matched task concept is decomposed to sub-tasks through a method selected in terms of the invocation possibility by users at given user activity, and applications associated with task concepts are presented as selected applications.

We implemented the control method for the prototype of user activity-aware information delivery system for consumer in a commercial facility. We used the prototype for trial service for customers of a real department store. We constructed the instance user activity model that have more than 3000 rules. About 700 customers' evaluation results indicates that the instance user activity model is successfully constructed and the user activity-aware application selection control method is valid.

4 Conclusion

We aim to create new applications to be used in real world. Such applications have to deal with the effect of environment where users or systems are located. It is required to consider many factors that can have impact on the behavior of the applications, and network and system that support them. Therefore a method to control the behavior of an application, a network, and a system to have them adapt to conditions of the environments is inevitable. Building control methods for new environments, possibilities and constraints of that are not well known, becomes very important especially when conventional wireless networks or systems do not meet the requirements of the environments , and thus is set as the goal of the thesis.

Basic strategy for the building of our control method is first to construct a generic model representing environment conditions that applications, networks and systems are related to, then to establish the way to explore the effect of the change in conditions of surrounding environments on the applications, the networks, and systems, and to derive a guideline for the control method of the applications, the networks, and the systems.

As a first step to build a control method of wireless network adaptive to changes in conditions for varieties of environments, traffic load was focused as primal condition of environment. The impact of traffic load changes and the restriction of traffic load observation on the network performance were examined. We proposed a method for a link scheduling of a wireless mesh network that adapts to the change of average traffic demands at communication links. This method is based on a weighted graph coloring and we came up with new weight updating procedure to adapt to traffic demands change. We conducted data transmission simulations where traffic demands at randomly selected communication nodes increase to compare the adaptability of the proposed method and conventional methods to traffic demands increment. The upper bound of traffic demands increment where all data were successfully transmitted to destinations was investigated as an indicator of the throughput of the network. The upper bound is dependent on the percentage of nodes that increase traffic demands. When the percentage of nodes that increase traffic demands grows, the upper bounds decrease for the proposed method and an non-adaptive conventional method, however, the ratio of the upper bound of traffic demands increment of the proposed method to that of the non-adaptive conventional method were kept around 200% for all percentages. It is concluded that the proposed method acquired significant adaptivity for traffic demands increment compared to conventional methods. The effect of the restriction of traffic demands observation to limited nodes was also investigated. We examined the upper bounds of traffic demands for networks designed by the proposed method with four different types of traffic load observation restriction. All restricted networks did not show the adaptability when the percentage of the number of observable nodes is low, however as the percentage grows, the ratio of upper bound of traffic demands of each method to that of the non-adaptive method reaches 121% to 174%. Among the restrictions, the restriction to nodes with large traffic demands at initial time showed the superiority for most cases. Instead the restriction to nodes with complex network topology such as nodes connected to many communication links had network topology dependent disposition and did not achieve good performances in general. As a conclusion, the observation restriction to nodes with large traffic should be adopted if a restriction on the number of observable nodes is imposed for network implementation.

Context-aware application selection system has been focused as the target of our control method for application layer. Semantic model to describe user activities has been constructed to use for the selection of an application appropriate for a user activity. We treats a user activity as the performance of tasks necessary for solving a problem that the user encounters. The representation of a task of solving a large problem are decomposed into the representations of sub-tasks of solving the sub-problems decomposed from the large problem. Task itself is represented by task concept and its method using vocabulary of task ontology. Description of user activity model starts from the task at the level of large granularity. Next, methods to achieve the task are linked, and each of the methods is decomposed into a sequence of sub-tasks. This process continues until the granularity of task concepts reaches the granularity of available applications. The user activity model also features that it includes prevention tasks that prevent obstacles from happening, and solution tasks to solve the problems which have happened. We constructed generic user activity model that contains hundreds of general task concepts. We build instance level user activity model for a specific facility from the generic user activity model. This leverage the generic user activity model so that we can populate several thousand specific model relatively low cost with very few contradiction. An application is associated with an appropriate task concept in the instance model. Applications are considered methods to accomplish associated task concepts. It also becomes possible to use sensor data to detect some of instance level user activity. In this manner, our user activity model consists of generic user activity model and instance level activity models, and this enables both the wide coverage of user activity representations and sensor triggered semi-automated processing at the same time. This is the original feature of our user activity model.

Based on the user activity model we built application selection schema. A given target task is matched to the task concept in the user activity model, the matched task concept is decomposed to sub-tasks through a method selected in terms of the invocation possibility by users at given user activity, and applications associated with task concepts are presented as selected applications.

The method was applied to build a prototype of context-aware information delivery system for consumer in a real commercial facility. We constructed the instance user activity model that has more than 3000 rules. The prototype was used for a trial service provided for a real department store. About 700 customers joined the trial and their evaluation results indicate that the instance model is successfully constructed and the model construction method is valid.

The contribution of this thesis is the control methods based on the generic model of environment conditions that enables the investigation of the effect of environment conditions to an application, and an network and/or a system that support the application. Because of the generic model, the methods are very effective especially for new applications in new environments where conventional applications or networks are not supported.

There are a couple of remaining issues for each field. The control method for wireless network link scheduling handles with MAC layer problems. Networking layer and transport layer have to be taken into account to build a control method that can handle total performance of network. We focused traffic load as primal environment conditions. Error rate of communication links and variations of network topologies will be attacked next. The task ontology based service selection schema has high potential as a semantic level control mechanism of context-aware system. Applying the schema to other application domains are future issues.

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