Exploring Potential Human Activities in Physical and Virtual Spaces: A Spatio-temporal GIS Approach

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Abstract

Opportunities of potential human activities have extended from physical space to virtual space in today’s society. Based on a proposed conceptual framework that models the relationships between physical and virtual spaces, this paper presents an attempt to adjust the space-time prism concept of Hagerstrand’s time geography to identify potential activity opportunities in virtual space, focusing on virtual space access channels in physical space. A three-dimensional (3D) spatio-temporal geographic information system (GIS) design is then developed to accommodate the adjusted space-time prism concept and support the effective representation, visualization, and analysis of potential human activities and interactions in physical and virtual spaces using the prism representation. Following the design, a prototype system is successfully implemented in a 3D GIS environment. Such a system will offer powerful analysis tools for studies related to potential human activities and applications such as location-based services (LBS) and accessibility analysis in the information age.

Keywords: spatio-temporal GIS, human activity, time geography, adjusted space-time prism

1. Introduction

Identifying potential human activities is an important task for a variety of research fields, such as accessibility studies, transportation planning, and location-based services. From a geographic perspective, potential human activities can be defined as available opportunities for an individual to conduct and complete certain tasks within a space and time context. Normally, these opportunities are physically separated from people who need them. Travel, therefore, is required to help people overcome the physical separation and reach the opportunities (Hanson 1995). Both travels and activities take time. As time is a limit resource, more time for travel means less time available for an individual to perform activities. Thus, the performance of human activities is constrained by both space and time. Hägerstrand's (1970) time geography provides a useful framework to investigate human activities with their space-time constraints in an integrated system of space and time. The framework has been adopted in a number of studies related to human activities and their spatio-temporal patterns (see Lenntorp 1976, Carlstein *et al.* 1978, Parkes and Thrift 1980, Carlstein 1982, Ellegård 1999). As one of its major contributions, time geography provides an effective concept, *space-time prism*, to portray potential human activities in physical space. A space-time prism depicts the extent in space and time that is physically accessible to an individual under a set of constraints (Lenntorp 1976). Using this framework, a person's opportunities for potential activities in physical space and time can be delimited by a space-time prism. Furthermore, the opportunities for potential interactions among people can be derived by examining the spatio-temporal relationships among the prisms of the participants (Miller and Shaw 2001).

In recent decades, our society experienced rapid developments of information and communication technologies (ICT), such as the Internet, cellular phones, and wireless-enabled personal digital assistants (PDA). Accompanying the developments of ICT, the number of ICT service providers and their users are growing at a fast rate. According to an Internet domain survey conducted by the Internet Systems Consortium (2006), the number of Internet hosts increased nearly eleven times from 29.67 million in January 1998 to 353.3 million in July 2005. During the thirteen years from 1991 to 2004, subscribers of cellular phone services and the Internet users in the world have increased dramatically, from 16 million to 1752 million for cellular phone customers and from 4.4 million to 870 million for Internet users (International Telecommunication Union, 2006). The growing use of ICT has altered how people carry out their activities and how they interact with each other, and this has caused changes in spatial and temporal distribution of potential human activities.

The wide adoption of ICT in today's society has created a parallel virtual space in addition to the conventional physical space. The virtual space, also called cyberspace, depends on the infrastructures and facilities of ICT that reside in physical space (Janelle and Hodge 2000). This space can carry information flows efficiently and enhance the connections between people through electronic linkages. Different from physical space, which is made of atoms, virtual space is composed of bits of information (Negroponte 1995). Virtual space allows people to exchange information while they are at different locations (e.g., calling a friend in a different city). It enables a new mode for people to be involved in an activity remotely. This mode is known as *tele-presence* in the literature (Janelle and Hodge 2000) and it is different from the conventional *physical presence*, which requires a participant to be physically present at an activity location. With tele-presence, an individual can sense and influence the environment in a spatial extent that is far beyond his/her physical proximity (Adams 1995, 2000, Kwan 2000). Thus, with the existence of both physical and virtual spaces in today's society, the opportunities of potential activities to an individual can exist not only at locations within the physical proximity of the individual but also where this individual can reach through tele-presence. Current time-geographic framework can portray potential human activities in physical space. However, it falls short of providing a complete framework of handling potential activities in today's society. The framework therefore should be modified to deal with potential human activities in both physical and virtual spaces.

Time-geographic framework has a well-defined structure. However, partially due to the limited computational power in the past, it was used primarily as a conceptual model in most studies with limited progress in implementing it with computational models (Yuan *et al.* 2004). Geographic information systems (GIS), which are designed to efficiently handle spatial data and solve spatial problems, have been considered as a potential approach to operationalizing time-geographic concepts. Miller (1991) implemented the space-time prism concept in a GIS environment to study individual accessibility, with GIS procedures to calculate feasible space in a network that is accessible to an individual under specific space-time constraints. Recently, several more attempts have been made to use GIS for measurements of individual space-time accessibility and identifications of available opportunities (Kwan and Hong 1998, Miller 1999, Miller and Wu 2000, Weber and Kwan 2002, Kim and Kwan 2003, Weber 2003). These attempts provide valuable experience in representing activities with their spatio-temporal characteristics in GIS. However, a GIS framework, which can provide an integrated space-time representation to support time-geographic analyses of human activities and interactions in physical and virtual spaces, has not been developed. Conventional GIS is originated from the cartographic view, which models the geographic phenomena as static spatial features on the ground (Spaccapietra 2001, Peuquet 2002). Such a static approach introduces fundamental deficiencies in providing an effective environment to implement the time-geographic framework, which involves interactions between space and time. Current GIS design needs to be extended so that it can explicitly handle spatial and temporal characteristics of time-geographic concepts. In this paper, a spatio-temporal GIS design is proposed to accommodate an adjusted space-time prism concept and to support representation, visualization, and exploratory analysis of potential human activities in both physical and virtual spaces.

The remaining parts of this paper are organized into five sections. The next section discusses potential human activities and their spatio-temporal constraints. Based on the discussions, an adjusted space-time prism concept is developed to describe potential activities in physical and virtual spaces. Section 3 focuses on the design of a spatio-temporal GIS framework to support representation, visualization, and exploratory analysis of the adjusted space-time prism concept for studying potential human activities and interactions in today’s society. Section 4 presents a prototype GIS implementation of the proposed framework. Examples of space-time prisms and results of spatio-temporal analysis created in the prototype system are described in this section. The final section concludes with a discussion of potential applications of the framework and future research directions.

2. Potential human activities and spatio-temporal constraints

Space and time are two essential factors that serve as constraints on planning and carrying out human activities. Every activity has its specific characteristics in space and time. Before the wide spread of ICT, physical space was the predominant stage for people to conduct activities and interact with others. An individual was required to be physically present at a location in order to participate in an activity or interact with other people. Thus, an activity is considered a potential activity to an individual only if the venue of the activity is physically accessible to the individual under a specific set of constraints. The space-time prism concept in Hägerstrand's time geography provides an effective model to identify such opportunities under spatio-temporal constraints. The extent delimited by a space-time prism indicates where and when an individual can conduct activities. Considering time as an equal term as space, time geography adopts a 3-dimensional orthogonal coordinate system (2D for space and 1D for time) to investigate the relationship of space and time in constraining human activities (Hägerstrand 1970). Figure 1 shows a typical space-time prism with fixed origin (L_1) and destination (L_2), and a time window of (t_2 - t_1). Its projection on the 2D plane is a region, which is known as *potential path area* (Lenntorp 1976). If an activity takes place at a location during a time window that falls within the extent (e.g., activity *a* in Figure 1), the person will be able to participate in this activity with a journey starting from the origin and ending at the destination within the given time window (i.e., between t_1 and t_2). As activities *b* and *c* are located outside the extent of the space-time prism, this person will not be able to conduct those activities under the given constraints. Hence, the space-time prism concept of Hägerstrand's time geography can be used to investigate an individual's potential activities in physical space.

With the emergence of virtual space, an individual can participate in activities remotely through tele-presence. In this case, spatial constraints are alleviated for these activities. Therefore, activities conducted in virtual space will not have the same constraints as those conducted in physical space. In other words, under the same set of space-time constraints, an individual with access to virtual space will have a different set of potential activity opportunities than an individual without access to virtual space. It therefore is important to study the relationships between physical space and virtual space and their implications to an individual's potential activity opportunities in these two spaces.

2.1. Physical space vs. virtual space and physical activity vs. virtual activity

Physical space and virtual space have different characteristics. Negroponte (1995) views physical space as a material world made of atoms and virtual space as a world composing of bits of information. While physical space serves as a container for both physical materials and information, virtual space is specialized in transmitting flows of information efficiently. Movements of materials in physical space usually take a significant amount of time, while information can be transmitted in virtual space with an amount of time that is negligible to most people. As activities in physical space are distributed at different locations, travel is usually required for an individual to conduct each activity (Hanson 1995). Therefore, an individual has to manage and balance the time spent between travels and activities such that s/he is able to participate in activities at different locations. On the other hand, activities in virtual space allow people to be involved through tele-presence. As long as an individual has access to virtual space, physical locations play a less significant role on activity participations. When tele-presence is used in lieu of physical presence, an individual can save time from making physical movements and therefore gains a greater flexibility of activity participations. In this study, we use *physical activities* and *virtual activities* for activities conducted in physical and virtual spaces, respectively.

Batty and Miller (2000) argue that these two spaces share intersections and influence each other despite their differences. Research has shown that activities in physical space and virtual space can influence each other (Salomon 1986, Shen 1998). Although tele-presence reduces the significance of distance in activity participations, physical space still controls where an individual can access virtual space since the access to virtual space is not ubiquitous in physical space yet. Also, information flows in virtual space can influence activities carried out in physical space. For example, cellular phones allow us to arrange our interactions with other people more spontaneously (e.g., arrange meeting place and time on the fly). Also, the information gathered or activities performed on the Internet can influence our activity and travel decisions (e.g., search for comparative product information or perform an e-banking transaction on the Internet).

This study proposes a conceptual framework to illustrate the roles of and interactions between physical space and virtual spaces (Figure 2). Both physical and virtual spaces could be considered relatively independent because each space has its own specific characteristics of handling activities within its domain. Transportation helps people move around in physical space, while ICT provide the means for people to navigate in virtual space. The two spaces are not really separated from each other; they intersect and influence each other through the intersection. Two aspects of the intersection are identified in this study. On the one hand, physical space provides access channels to virtual space because virtual space is enabled by information and communication infrastructures residing in physical space. Thus, if an individual wants to perform virtual activities, s/he has to reach these access channels in physical space. Consequently, movements in physical space may be required to help the individual find the access channels and connect to virtual space. In the meantime, virtual space can feed information back to physical space. The information can be retrieved from virtual space and can impact the physical activity patterns through decisions made by the individuals participating in virtual activities.

Based on the proposed conceptual model, physical space plays two roles in supporting human activities: it serves as a *carrier of physical activities* as well as a *connector for virtual activities*. Being a carrier of physical activities is the conventional role that physical space plays in supporting physical activities. The space-time prism concept of Hägerstrand’s time geography provides an effective approach to dealing with the relationship of physical activities with their space-time constraints. For virtual activities, on the other hand, physical space serves as a connector to provide people with access channels to virtual space and supports virtual activities by hosting ICT infrastructures and facilities. This role of physical space has not been sufficiently addressed in Hägerstrand’s time-geographic framework.

Potential human activities in today’s society include activities in both physical and virtual spaces. The original space-time prism concept can be used to delineate the extent of potential physical activities in space and time. However, the concept needs to be adjusted to describe the opportunities of potential virtual activities in space and time. When people attempt to conduct virtual activities, they must connect to virtual space. As access channels to virtual space are not ubiquitously available in physical space, physical presence at a location with access channels is a necessary condition for people to conduct virtual activities. Subsequently, physical movements undertaken to reach the access channels become a prerequisite for most virtual activities. Conducting activities in virtual space therefore is still controlled by constraints in physical space and time. Here we develop an *adjusted space-time prism* concept for virtual activities, which describes the opportunities in physical space that allow an individual to connect to virtual space and carry out virtual activities under a set of constraints. In other words, the identification of potential virtual activities is considered as a process of locating virtual space access channels in physical space under certain space-time constraints.

2.2. Adjusted space-time prisms for locating potential virtual activities

Based on the definition of an adjusted space-time prism in this study, the prism can be achieved by intersecting a conventional space-time prism with *space-time life paths* of virtual space access channels in physical space. In this study, the term *space-time life path* is used to describe the existence of a virtual space access channel in space and time. Unlike a space-time path, which portrays an individual's trajectory, a space-time life path represents a virtual space connection service at a specific space-time extent. A space-time life path is constructed by extruding a virtual space access channel along the time dimension based on its operational hours. Therefore, it represents the time period during which individuals can access virtual space from a specific location.

Two types of virtual space access channels, *wired access channels* and *wireless access channels*, are identified in this study according to their connection methods to virtual space. *Wired access channels* provide connections to virtual space at fixed portals, such as fixed phone lines and wired Internet ports. This type of virtual space access channels usually resides at fixed locations and can be considered point-like geographic features. *Wireless access channels* offer connections to virtual space within continuous regions instead of at discrete locations. An individual with suitable ICT devices can access virtual space from any location within the region. A cellular phone service area and a wireless network covering area are typical examples of this type of access channels. Wireless access channels are represented as areal geographic features. Based on these two types of virtual space access channels, the space-time life paths of these access channels can be modeled into two forms, s*pace-time life lines* and *space-time life cylinders*. Space-time life lines, which are constructed by extruding point access channels along the time dimension, are used to represent the space-time life paths of wired access channels. Space-time life cylinders, which are constructed by extruding areal access channels along the time dimension, are the form of space-time life paths for wireless access channels.

Two types of adjusted space-time prisms for virtual activities can be achieved according to these two types of virtual space access channels by intersecting the conventional space-time prism with their corresponding forms of space-time life paths. Figure 3a shows the adjusted space-time prism for virtual activities with wired access channels. The conventional space-time prism demarcates the space-time extent that an individual can reach under the given constraints. Three wired access channels are located at different locations (f_1, f_2, and f_3). Their space-time life paths are represented as space-time life lines, which are shown as thick dashed lines in Figure 3a. While both f_1 and f_3 have 24-hour access to virtual space, f_2 provides access only after a certain time. The space-time life lines of f_1 and f_2 intersect with the conventional space-time prism and their intersections are shown as thick solid lines in Figure 3a. The thick solid lines indicate that the person has opportunities to reach these two locations, access virtual space, and conduct virtual activities. The time window for accessing virtual space at each location is indicated by the length of the line segment, with its ends marking starting and ending times. Therefore, the adjusted space-time prism with wired access becomes a collection of vertical line segments in the 3D coordinate system. Figure 3b demonstrates the case of wireless access channels. The space-time life path of a wireless access channel is represented with a space-time life cylinder in the figure and the cylinder intersects the conventional space-time prism. The intersection depicts the opportunities where and when an individual can accessed virtual space to conduct virtual activities. The adjusted space-time prism for virtual activities with wireless access differs from that with wired access in that it has a continuous extent in space and time. A person can continue to access virtual space while moving around within those confines.

2.3. Potential human interactions in physical and virtual spaces

People are social beings and need to interact with others. A significant part of our daily activities involve multiple participants and require interactions among them. Being able to identify opportunities for potential human interactions are of great interests to researchers in various studies. While potential activities of a single person can be described with a single space-time prism, the identification of potential interactions among people requires analyses on the spatio-temporal relationships of their prisms. As people can be involved in an activity through different modes (i.e., physical presence and tele-presence), various spatio-temporal patterns exist for these interactions (Golledge and Stimson 1997).

Four types of communication modes have been suggested in the literature based on their different spatial and temporal characteristics (Table 1; see Janelle 1995, Harvey and Macnab 2000, Miller 2003). Conventional face-to-face meetings require participants to be at the same location during the same time period. This type of communications, which requires coincidence in both space and time or a spatio-temporal relationship of *co-existence* among participants, is classified as *Synchronous Presence* (SP). Communications such as leaving notes on a bulletin board require people to visit the same location to complete the information exchange, but they can be at the same location at different times. This type of communications is called *Asynchronous Presence* (AP), as it requires coincidence only in space, not in time. People involved in this type of communications share a spatio-temporal relationship of *co-location in space*. With the tele-presence enabled by ICT, people are no longer required to be present at the same physical location. *Synchronous Tele-presence* (ST) communications only require coincidence in time (e.g., a videoconference with participants at different locations), which create a spatio-temporal relationship of *co-location in time*. Finally, *Asynchronous Tele-presence* (AT) communications are free from coincidence requirements in both space and time. E-mail contacts belong to this type of communications. People involved in such communications have a spatio-temporal relationship of *no co-location in either space or time*.

These spatio-temporal relationships can be used to examine the opportunities for potential interactions among people because different types of human interactions require different spatio-temporal relationships among their participants. As SP and AP interactions take place in physical space only, conventional space-time prisms are sufficient to investigate the potential interactions among individuals. If the conventional space-time prisms of two individuals overlap as shown in Figure 4a, it indicates that the individuals can reach the same location during the same time (i.e., co-existence); therefore, they can carry out potential SP interactions. The overlapping area (shown as shaded area in Figure 4a) depicts the extent in space and time for the opportunities of potential SP interactions between the individuals. Figure 4b shows that two conventional space-time prisms overlap on the space dimension, which indicates that these individuals will be able to reach the same locations (i.e., co-location in space) during different time windows. Such situations provide opportunities for individuals to carry out AP interactions. The shaded areas of prisms in Figure 4b demarcate the space-time extent for each individual to conduct potential AP interactions at the locations. Both ST and AT interactions involve activities in virtual space. Therefore, adjusted space-time prisms are needed to examine opportunities of these interactions. The gray areas of the space-time prisms in Figure 4c and 4d indicate the space-time extents with access to virtual space. ST interactions require participants to access virtual space at the same time, while having no requirements for locations (i.e., co-location in time). If two individuals' prisms for virtual activities overlap on the time dimension as shown in Figure 4c, these individuals will have opportunities to conduct ST interactions. The shaded areas within the prisms for virtual activities depict the opportunities in space and time that allow ST interactions among the individuals. AT interactions do not require coincidence in either space or time (i.e., no co-location in either space or time). As long as participants have access to virtual space and the receiver of an AT interaction has access to virtual space at a later time than the initiator, they will be able to conduct AT interactions. Figure 4d illustrates the situation for potential AT interactions, which shows that the receiver's adjusted space-time prism needs to last beyond the earliest boundary of the initiator's prism on the time dimension and the receiver has a chance to pick up the incoming message. These spatio-temporal relationships between prisms provide an approach to exploring potential human interactions in both physical and virtual spaces.

3. Spatio-temporal GIS design to support the exploration of potential human activities and interactions

Representation plays an important role in problem solving using a computer system (Winston 1984). A proper representation of space-time prisms is critical to the GIS design in support of exploring potential human activities and interactions. An efficient representation of space-time prisms in GIS requires an integrated and explicit representation of space and time. Current GIS design is based on a 2D and static representation of geographic phenomena and must be extended to handle both space and time.

Spatio-temporal GIS research has been an active topic since the late 1980s (Renolen 2000). Several major approaches have been proposed to represent space and time in GIS, which include snapshot model (Armstrong 1988), space-time composite model (Langran and Chrisman 1988, Langran 1992), object-oriented approach (Worboys 1992, 1994), event-based approach (Peuquet and Duan 1995), and three-domain model (Yuan 1996). These approaches demonstrate various ways to represent space and time in GIS. However, they are not good candidates to efficiently and effectively represent space-time prisms. A specific spatio-temporal GIS design is developed in this study to represent the space-time prism concept.

3.1. A GIS environment to support the representation of space-time prisms

Hägerstrand's time geography adopts an orthogonal 3D coordinate system to study the spatial and temporal constraints of human activities, with 2D for space and 1D for time (Hägerstrand 1970). A 3D spatio-temporal GIS framework is designed in this study to simulate the coordinate system of time geography and support the representation of space-time prisms. Since these features reside in a space-time framework, they are named *spatio-temporal features* in this study. Figure 5 shows how these spatio-temporal features are represented in the spatio-temporal GIS framework. A spatio-temporal point feature, which occupies a single position in the 3D framework, is represented with a triplet of $<x, y, t>$, where x and y specify a location on a 2D space and t indicates a specific time. A spatio-temporal line feature is represented as a sequence of triplets ($\{<x_0, y_0, t_0>, <x_1, y_1, t_1>, \ldots , <x_n, y_n, t_n>\}$, where $t_0 < t_1 < \ldots < t_n$). A spatio-temporal 3D feature is an object that does not change shape in 2D space during its lifetime and has homogeneous properties in both space and time. It can be considered as a feature derived from extruding a feature in 2D space along the time dimension.

3.2. Generation and representation of space-time prisms

A space-time prism defines the extent in space and time that is accessible to an individual under specific constraints. The space-time prism of Hägerstrand’s time geography employs a continuous representation of space. Such an approach implies that every location in the space is navigable by people. However, people usually move along road networks and activities take place at particular locations (Miller 1991). Therefore, it is more meaningful and realistic to implement the space-time prism concept with a discrete network representation (Miller 1991, Kwan and Hong 1998). The network-based approach has been widely adopted in accessibility studies to calculate space-time prisms and potential path areas in GIS (Miller 1991, 1999, Kwan and Hong 1998, Miller and Wu 2000, Weber and Kwan 2002, Kim and Kwan 2003, Weber 2003). This study takes the network-based approach too and operationalizes the concept of space-time prism in a 3D GIS design.

Two cones are used to define the boundary of a space-time prism when constraints present at both the origin and the destination. One cone starts from the origin and moves upward along the time dimension; the other begins at the destination and runs downward. In this study, the two cones are called the *forward cone* and the *backward cone,* respectively. A forward cone depicts the range in space that could be reached by an individual from the origin with a given time budget. For each point on the cone, the time value of the point indicates the earliest time that an individual could reach this location from the origin. Similarly, the backward cone defines the range in space within which an individual could start out and travel to the destination within a given time budget. A shortest-path tree algorithm, which can help define the range that an individual could reach on a network from a given location with a given time budget, has been frequently used to compute network-based potential path areas (Miller 1991, Kwan and Hong 1998). The algorithm is also used in this study to compute the cones that define the boundary of a space-time prism.

Figure 6 shows how a network-based space-time prism is represented in the 3D GIS design. An individual travels on a road network and faces time constraints at both origin and destination. The person leaves the origin location L_1 at time T_1 and must return to the same location by time T_2. The shortest-path trees from the origin and to the destination can be calculated respectively. The travel time to any node in the network from the origin (L_1) can be derived from the shortest-path tree. For example, the travel time from the origin (L_1) to location L_2 is t_1. For any location on the network links, travel time to the location can be interpolated. Therefore, for any location in a network, it is possible to compute the time when the individual can reach the location. In Figure 6, an individual starts from the origin (L_1) at time T_1 and the travel time to location L_2 is t_1. Thus, the time for this individual to reach location L_2 is $(T_1+ t_1)$. Similarly, if the individual wants to reach the destination (L_1) from location L_2 by time T_2, s/he needs to leave before the time $(T_2- t_2)$. If $(T_2- t_2) > (T_1+ t_1)$, it indicates that the person has some time to conduct activities at the location L_2. If $(T_2- t_2) < (T_1+ t_1)$, the location is unreachable to the person under the given constraints. Since every location in the shortest-path tree from the origin has a time value, the tree can be displayed in the 3D space-time system. The light gray lines in Figure 6 show the shortest-path tree from the origin and they represent the forward cone of the prism. The darker gray lines represent the shortest-path tree to the destination and they show the backward cone of the prism. Spatio-temporal line features are used to represent these lines. Therefore, a network-based cone is a collection of spatio-temporal line features in the 3D GIS design. For each node in the network where the time value from the backward cone is greater than that from the forward cone, i.e., $(T_2 - t_2) > (T_1 + t_1)$, a vertical spatio-temporal line is created at the location, starting at $(T_1 + t_1)$ and ending at $(T_2 - t_2)$ along the time axis. The length of this line indicates the time duration that the person can stay at the location to carry out activities. A set of vertical spatio-temporal lines therefore is used to represent a space-time prism (thick black vertical lines in Figure 6). The two cones, along with the vertical spatio-temporal lines, depict the feasible space-time extent in physical space that can be visited by the individual for potential activities.

An adjusted space-time prism for virtual activities is a subset of a conventional space-time prism that portrays the opportunities to an individual for accessing virtual space and conducting virtual activities. It is derived from intersecting a conventional space-time prism with the space-time life paths of the access channels to virtual space. Two types of space-time life paths are discussed in section 2.2: space-time life lines for wired access channels and space-time life cylinders for wireless access channels. They are represented as spatio-temporal line features and spatio-temporal 3D features respectively in the GIS design (Figure 7a). For a wired access channel, such as a fixed Internet portal, a vertical spatio-temporal line is created at that location (e.g., at location L_1 in Figure 7a). The two ends of the line indicate the operation hours of the facility. For example, the wired access channel at location L_1 is available from t_1 to t_2. For a wireless access channel, such as a wireless network service area, a spatio-temporal 3D feature is used to portray its availability in space and time. In this study, it is assumed that the shape of the service area does not change over time. Therefore, the spatio-temporal 3D feature for a space-time life cylinder can be represented by extruding the shape of a service area in the 2D plane along the time dimension according to the operation hours of the access channel. With representations of space-time life paths for virtual space access channels, space-time prisms for virtual activities can be derived by intersecting space-time life paths with conventional space-time prisms (Figure 7b). Those spatio-temporal lines, which overlap with space-time life lines or fall within space-time life cylinders, indicate where and when an individual can reach virtual space access channels and conduct virtual activities. This subset of vertical spatio-temporal lines from a conventional space-time prism is used to represent the prism for virtual activities.

3.3. Exploration of potential interactions through spatio-temporal relationships of prisms

A space-time prism depicts feasible opportunities in space and time that are available to an individual to conduct potential activities. In order to identify potential interactions between individuals, we need to examine the spatio-temporal relationships of prisms between individuals. This requires the development of analysis functions in the spatio-temporal GIS design to help identify the spatio-temporal patterns of prisms. Since vertical spatio-temporal lines are used in this study to represent prisms for both physical and virtual activities, the analysis functions can be implemented by examining the spatio-temporal line features according to the four spatio-temporal relationships discussed in section 2.3.

If two prisms overlap with each other in the 3D GIS environment, the result will be a new set of vertical spatio-temporal lines representing feasible opportunities between the individuals to carry out potential SP interactions (i.e., co-existence relationship). If two prisms overlap on the 2D spatial dimensions, but not on the time dimension, we have a co-location in space relationship between the prisms. In other words, one individual visits a location first and the other individual visits the same location at a later time. The two individuals, therefore, can carry out potential AP interactions. For potential ST and AT interactions, tele-presence is involved and the adjusted prisms for virtual activities are required in the analysis. Identification of potential ST interactions (i.e., co-location in time relationship) involves a process of determining whether different sets of vertical spatio-temporal lines overlap on the time dimension. The overlapping time period is determined by comparing the minimum and maximum time values (i.e., begin time and ending time) of the spatio-temporal lines representing the prisms for virtual activities. The subset of each prism falling within the overlapped time period then is extracted to form a new set of vertical spatio-temporal lines. The result portrays the potential ST interaction opportunities among the individuals.

The relationship of no co-location in either space or time describes the spatio-temporal pattern of individuals engaging in AT interactions. If an individual has an opportunity to access virtual space after another individual initiates an AT interaction, they can participate in potential AT interactions. In other words, if the time span of an individual’s prism for virtual activities falls at least partially after the minimum time value of another prism of an individual who initiates an AT interaction, the two individuals will be able to engage in AT interactions. Again, by comparing the vertical spatio-temporal lines representing different prisms, we can determine the minimum time value in the prism of a potential AT interaction initiator and extract portions of other prisms falling after the time value. The extracted sets of vertical spatio-temporal lines portray the feasible opportunities for the individuals to engage in potential AT interactions with the initiator.

4. A prototype system implementing the design

With the adjusted space-time prism concept and the spatio-temporal GIS design proposed in this study, a GIS prototype system is developed to test the concepts and the GIS design. ArcGIS and ArcObjects are chosen as the development environment in this study because the ArcScene module in ArcGIS supports representation and visualization of 3D spatial features and ArcObjects offers a programming environment to develop new spatio-temporal analysis functions. By using *z* values for the time dimension, the ArcScene is adapted to simulate the space-time framework of time geography. Therefore, spatio-temporal point and line features are represented as point and line features with *z* values respectively, and spatio-temporal 3D features are represented as MultiPatch features in ArcGIS.

Road network of Knox County, Tennessee, is used in the prototype system. All travels and activities are assumed to take place on the road network. The prototype system supports the generation of spatio-temporal features (e.g., computing space-time prisms for individuals and creating space-time life lines and cylinders for virtual space access channels), visualization of spatio-temporal features and their interactions, and analysis of spatio-temporal relationships of prisms.

4.1. Creating network-based conventional space-time prisms

The prototype system provides interfaces to create conventional space-time prisms based on a road network under a set of user-specified space-time constraints. Dijkstra’s shortest path algorithm is implemented in the prototype system to search for shortest paths using the *ForwardStar Class* in ArcObjects (Zeiler 2002). Figure 8 shows a space-time prism, with both forward and backward cones created by the prototype system, for an individual who plans to leave the origin location at 3:00PM and would like to be at the destination by 3:20PM under an assumed average travel speed of 15 mph. The forward cone is shown with red lines and the backward cone is shown with green lines. The prism is represented with vertical purple lines confined by the two cones. The purple lines indicate where the individual can visit under the constraints, and the length of each purple line indicates how long s/he can stay at that location to conduct activities.

4.2. Creating space-time life paths and space-time prisms for virtual activities

To derive adjusted space-time prisms, the system requires space-time life paths representing the access channels to virtual space besides the conventional prisms. Wired accesses, such as landline phones and fixed Internet ports, are stored as point features. Wireless accesses, such as cellular phone service areas and wireless computer network coverages, are represented as polygon features in GIS (see Figure 9a). Based on the operation hours of these virtual space access channels, the GIS prototype system creates spatio-temporal features for their space-time life paths by extruding these features along the time dimension according to their operation hours. Subsequently, space-time life lines of wired accesses are represented as vertical spatio-temporal line features and space-time life cylinders of wireless accesses are represented as spatio-temporal 3D features (see Figure 9b).

An adjusted space-time prism is a subset of a conventional space-time prism that has access channels to virtual space. This subset can be generated by intersecting the space-time life lines/cylinders of virtual space access channels with the conventional space-time prism. In the prototype system, this operation is performed by intersecting a set of spatio-temporal line features (a conventional prism) with another set of spatio-temporal line features (space-time life lines of wired accesses) or a spatio-temporal 3D features (space-time life cylinders of wireless accesses). Figure 9c displays adjusted space-time prisms generated from wired accesses and wireless accesses respectively (shown as red line segments in the figure).

4.3. Exploring human interactions through spatio-temporal relationships of prisms

The GIS prototype system also includes analysis functions to identify spatio-temporal relationships between prisms. They can be used to explore different types of potential human interactions. Figure 10 offers examples illustrating each of the four types of interactions. Figure 10a shows an example of potential SP interactions between the prisms of two individuals. The red lines represent the result of intersection between the two prisms. They indicate the spatio-temporal extents of potential opportunities for SP interactions (e.g., a face-to-face meeting) between the two individuals. Figure 10b illustrates an example for potential AP interactions. With prisms of an initiator and a receiver of AP interactions, the analysis function looks for overlaps in space between the prisms (i.e., co-location in space) and finds locations at which the time values in the receiver’s prism are after those of the initiator’s. All feasible locations are stored in a new point feature class as the result. The attribute table of the result layer contains two extra fields, which can be used as foreign keys to link each record in the result layer (i.e., a feasible location) to records in the two individuals’ prisms (i.e., vertical spatio-temporal line features at the same location). Therefore, the spatio-temporal characteristics of the two individuals’ possible stays at a feasible location can be retrieved from their prisms and used for further investigations. For example, the initiator of a potential AP interaction can stay at a particular location for five minutes while the potential receiver can stay at the same location for one minute. If an AP interaction requires both participants to stay at the location for at least two minutes, this location then is infeasible for this interaction. Figure 10c displays a case for potential ST interactions that require adjusted space-time prisms in the analysis. The GIS prototype system can find co-location in time relationship of the adjusted prisms by identifying the overlapping parts of the prisms for virtual activities along the time dimension. The red lines in this figure indicate the potential opportunities for ST interactions (e.g., phone calls) between the individuals. Finally, Figure 10d shows a case for potential AT interactions with prisms for virtual activities. GIS analysis function in the prototype system finds the minimum time value in the prism of the initiator and identifies the subset in the prism of the receiver that is eligible for potential AT interactions (i.e., the red lines shown in Figure 10d).

5. Conclusions

Virtual space enabled by ICT enhances our capabilities to conduct activities in more flexible and timely ways. Tele-presence in virtual space helps us overcome the barrier of physical distance and allows us to participate in activities and interact with others remotely. Potential human activities available for an individual are greatly expanded with these new interaction modes. The space-time prism concept of Hägerstrand's time geography, which provides an effective framework to identify potential human activities in physical space, is insufficient to deal with activities and interactions taking place in virtual space. Based on a proposed conceptual framework that defines the relationships between physical space and virtual space, this study provides an adjusted space-time prism concept to investigate potential virtual activity opportunities, focusing on virtual space access channels in physical space. A spatio-temporal GIS design is then developed to incorporate the adjusted space-time prism concept in a 3D GIS environment. The study also implements a prototype system based on the GIS design. The prototype system demonstrates the feasibility of the proposed GIS design and provides useful analysis functions to explore the potential opportunities of human activities and interactions in today's society.

The GIS design and prototype system developed from this study can be applicable to many studies related to human activities. For example, accessibility studies can use this system to examine the potential activity and interaction opportunities for an individual due to the use of ICT. The results from the analysis functions in the system can offer insights on re-examining the meaning of accessibility in the information age. Location-based services is another field that can benefit from this GIS design. Space-time prisms can help identify the potential activities available to individuals with different space and time constraints. The analysis functions of spatio-temporal relationships between prisms further provide methods to identify interaction opportunities between people. The analysis results can provide useful information to help plan and schedule location-based activities and services for individuals.

In today's society, activities can take place in either physical or virtual space and they interact and intertwine to fulfil each individual's needs and form a complex social system. The adjusted space-time prism concept proposed in this paper presents our initial effort to understand human activities in physical and virtual spaces and their complex interactions. According to the conceptual framework of relationships of physical space and virtual space illustrated in Figure 2, we can see that activities in virtual space are constrained by both the distribution of virtual space access channels in physical space (e.g., wireless network service areas) and conditions in virtual space (e.g., operation hours of an online class registration service). The adjusted space-time prism concept offers an effective method to identify access channels for potential virtual activities. Further effort is needed to investigate what are the constraints in virtual space and how they interact with access channels to impact an individual's opportunities of conducting virtual activities. Because transmitting information in virtual space takes far less time than in physical space, boundaries defining the opportunities in virtual space are no longer prisms in shape. Then, what is a logical form to represent the opportunities in virtual space under constraints and how can we represent it in GIS and develop functions to facilitate relevant analysis? This study can be extended to answer these research questions in the future. The conceptual framework also indicates that virtual activities can bring information to physical space and impact the pattern of physical activities. Researchers have found that virtual activities can have different effects on physical activities, including substitution, complementarity, modification, and neutrality (Salomon 1986, 1998, Mokhtarian 1990, Mokhtarian and Meenakshisundaram 1999). Activities are not independent to each other. Activities in physical space and virtual space intertwine to assist people in fulfilling goals in their daily lives. Therefore, it is nature to look into activities with their interrelationships rather than treat them individually. Although efforts have been made to implement the space-time path concept to effectively represent individual physical and virtual activities (Yu 2006) and the space-time prism concept to identify potential activity opportunities in GIS, modelling and representing the interrelationships between activities, especially between physical activities and virtual activities, remains a big challenge in the research field. A breakthrough will offer an effective and useful tool for researchers to investigate the relationships between physical and virtual activities and an opportunity to better understand spatio-temporal characteristics of human activities in the information age.

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Table 1. Communication modes based on their spatial and temporal constraints.
(Adapted from Miller 2003)

Temporal **Spatial**	**Synchronous**	**Asynchronous**
Physical presence	**SP** Face to face (F2F)	**AP** Post-it® notes Traditional hospital charts
Tele-presence	**ST** Telephone Online chat rooms Teleconferencing	**AT** E-mail Webpages

Figure list:

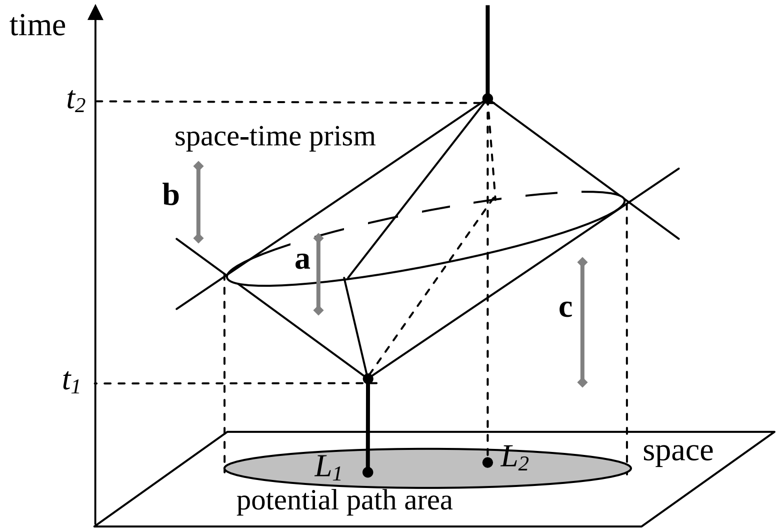


Figure 1. Space-time prism and potential path area

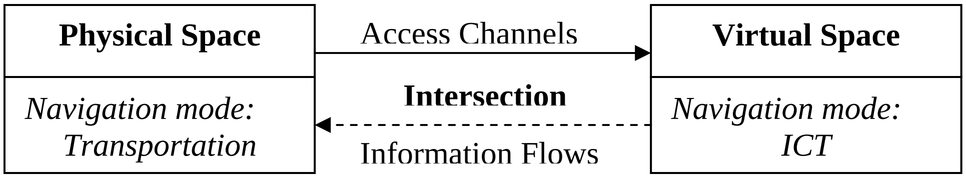
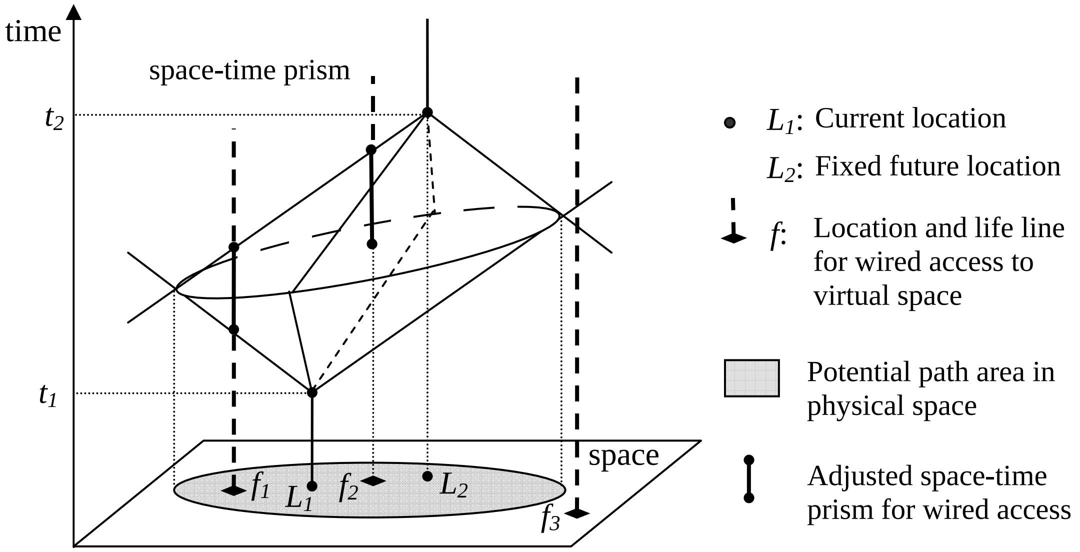
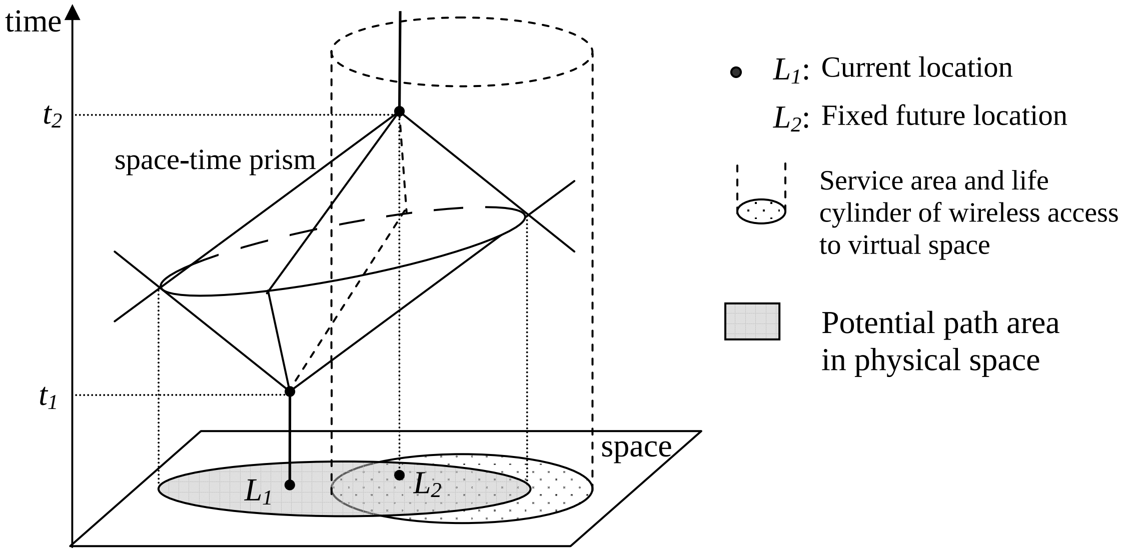


Figure 2. Relationships between physical space and virtual space

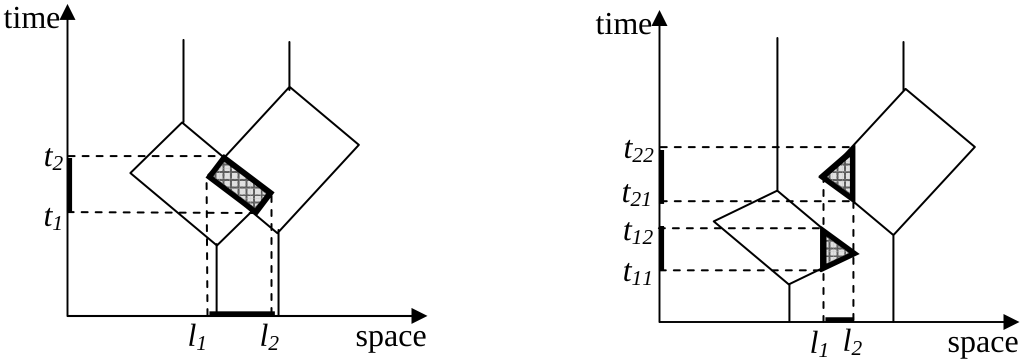


a. Space-time prism for virtual activities with wired access



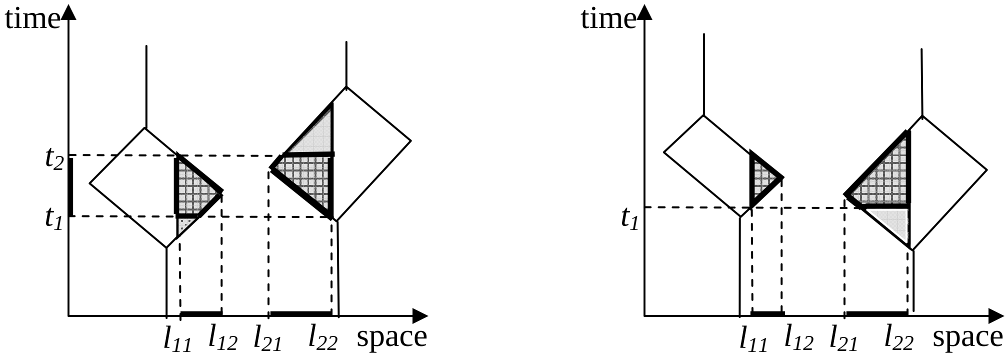
b. Space-time prism for virtual activities with wireless access

Figure 3. Adjusted space-time prisms for virtual activities



a. Potential SP interactions

b. Potential AP interactions



c. Potential ST interactions

d. Potential AT interactions

▭ **Adjusted space-time prism for virtual activities**

▦ **Subset of a prism suitable for potential interactions**

Figure 4. Spatio-temporal relationships of prisms and potential interactions.

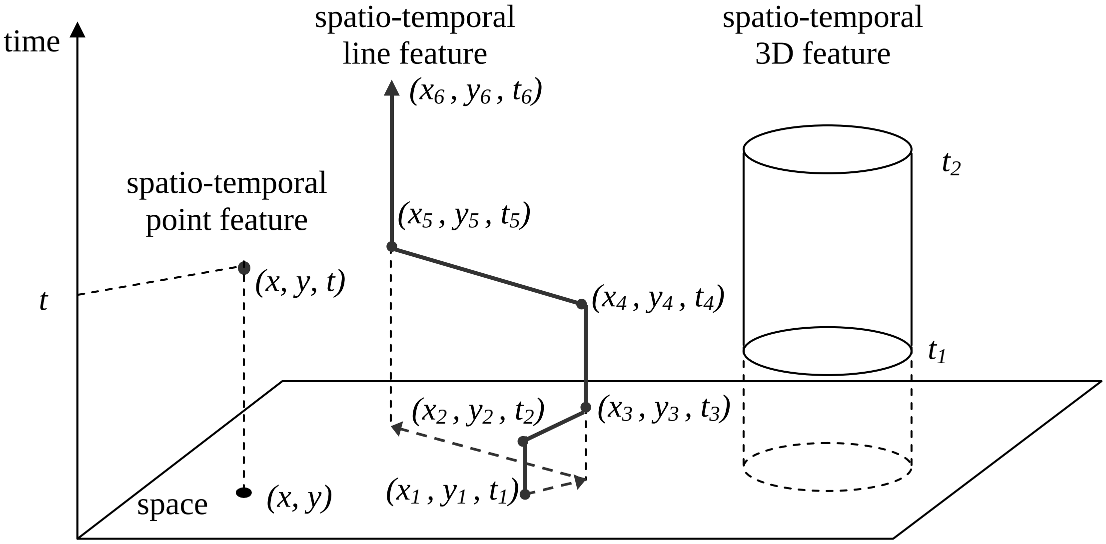


Figure 5. Spatio-temporal features in a 3D GIS framework

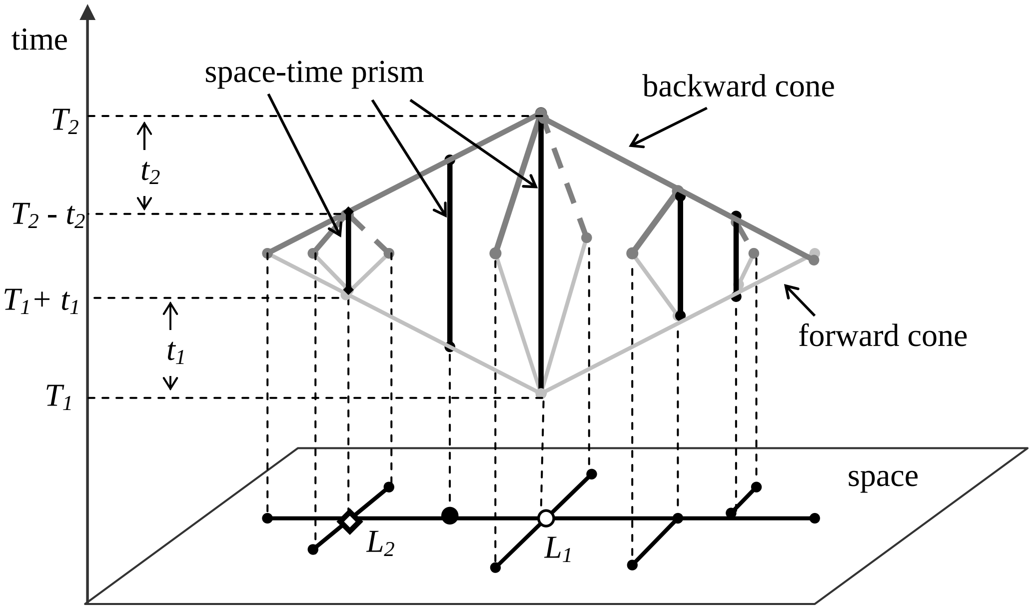
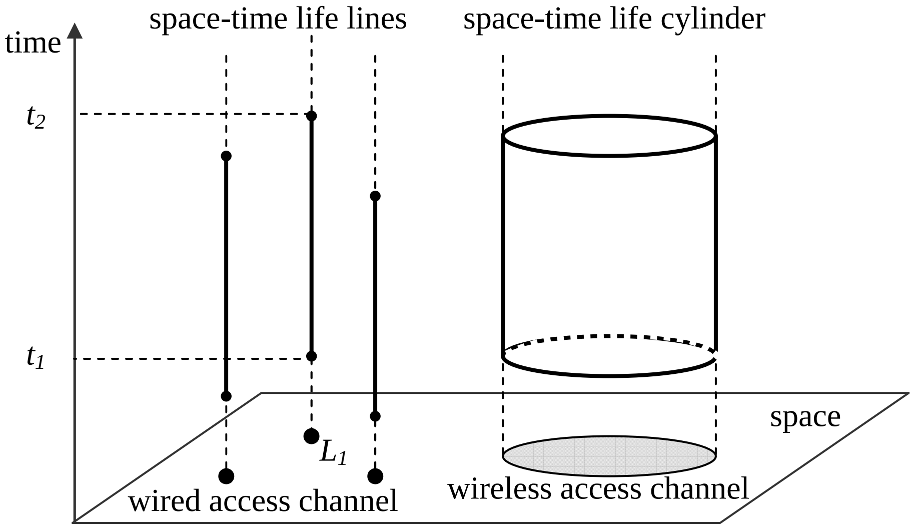
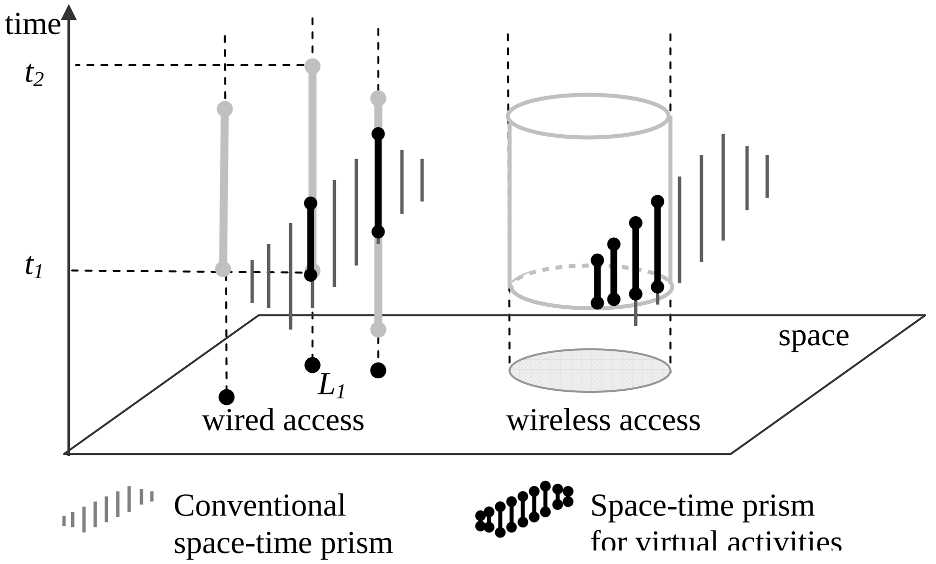


Figure 6. A 3D GIS representation of a network-based space-time prism.



a. Representing space-time life paths for virtual space access channels



b. Intersection space-time life paths with conventional space-time prisms

Figure 7. A 3D GIS representation of space-time prisms for virtual activities

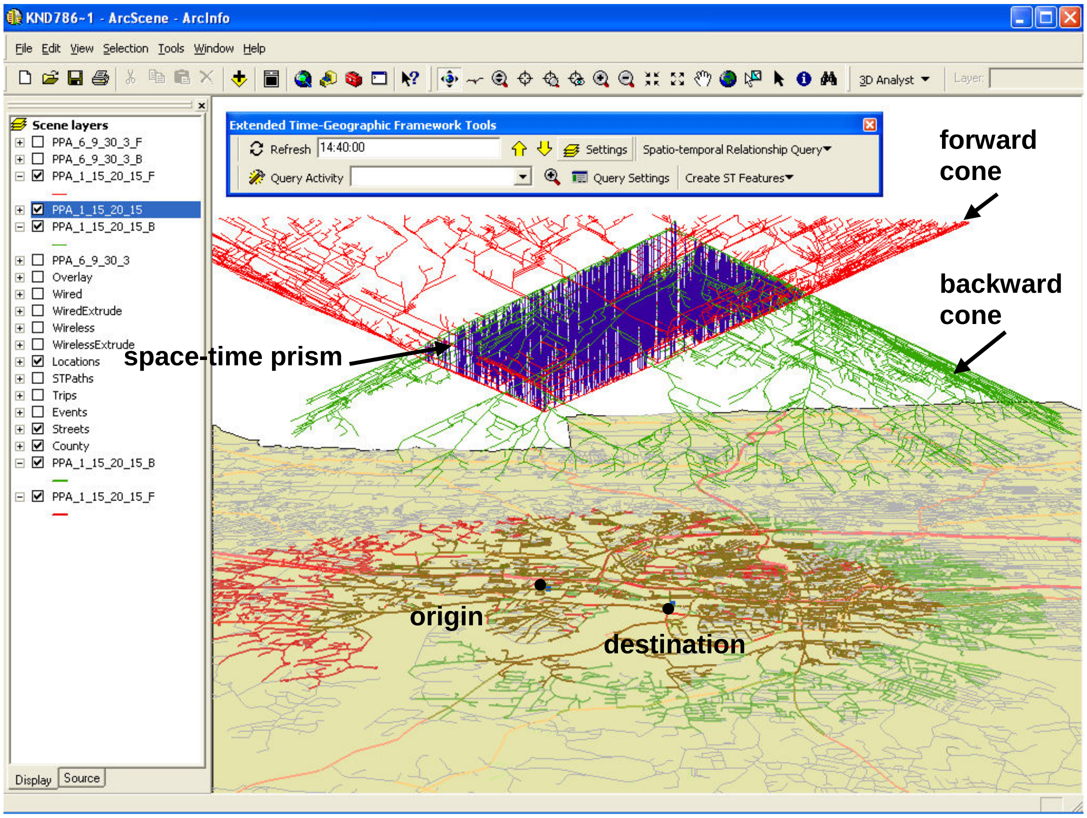
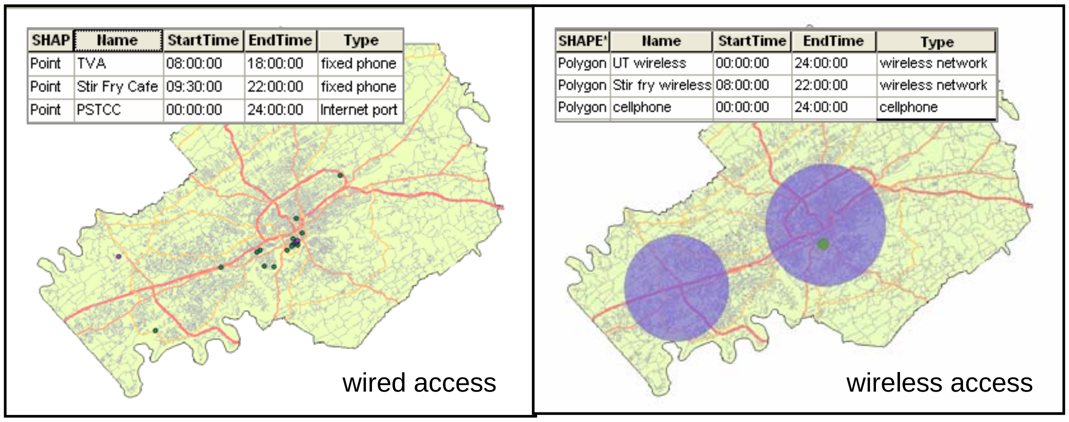


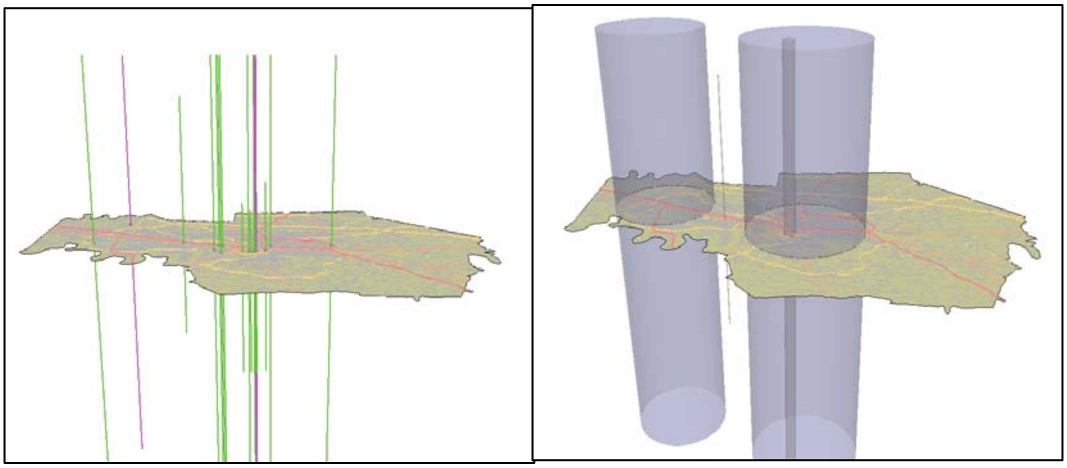
Figure 8. A case of space-time prism with constraints on both origin and destination



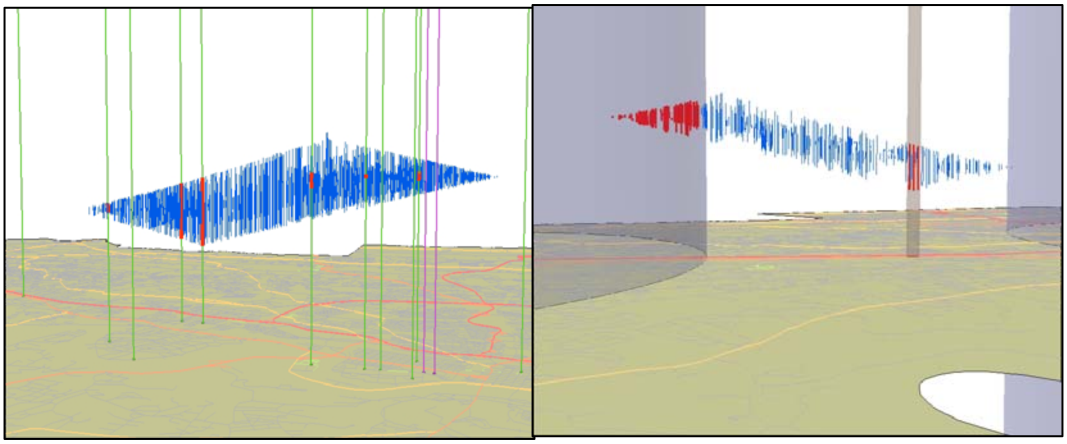
SHAP	Name	StartTime	EndTime	Type
Point	TVA	08:00:00	18:00:00	fixed phone
Point	Stir Fry Cafe	09:30:00	22:00:00	fixed phone
Point	PSTCC	00:00:00	24:00:00	Internet port

SHAPE'	Name	StartTime	EndTime	Type
Polygon	UT wireless	00:00:00	24:00:00	wireless network
Polygon	Stir fry wireless	08:00:00	22:00:00	wireless network
Polygon	cellphone	00:00:00	24:00:00	cellphone

a. Wired and wireless access channels

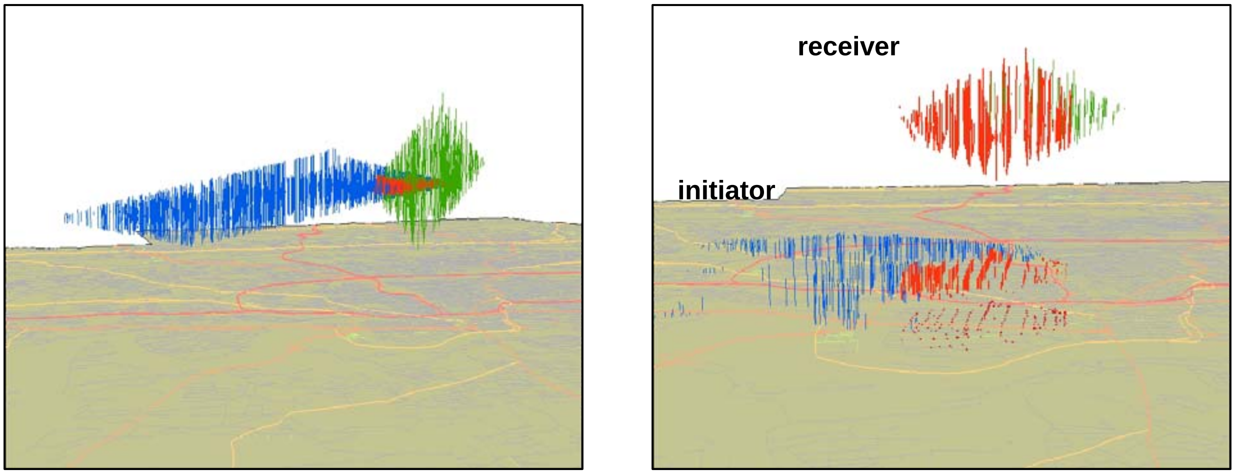


b. Space-time life lines and cylinders



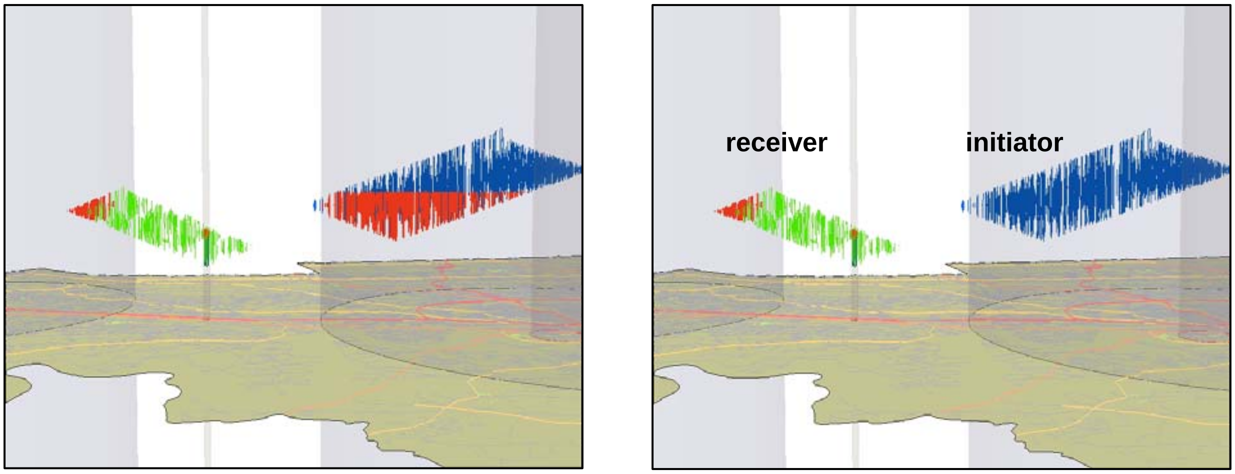
c. Space-time prisms for virtual activities

Figure 9. Space-time life paths and prisms for virtual activities



a. A case for potential SP interactions

b. A case for potential AP interactions



c. A case for potential ST interactions

d. A case for potential AT interactions

Figure 10. Spatio-temporal relationship analyses for exploring potential interactions