Potential effects of ICT on face-to-face meeting opportunities: a GIS-based time-geographic approach

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ARTICLE INFO

Keywords:
ICT
Face-to-face meeting
Time geography
Space–time GIS
Activity-based model

ABSTRACT

People in modern societies are increasingly experiencing the impacts of information and communication technologies (ICT) on their daily activities and their interactions with other people. These changing activity and interaction patterns due to the use of ICT have important implications to human activity and travel patterns. There are scant studies offering a spatiotemporal analytical framework that can help researchers examine the interactions between ICT and human activities at the individual level. Time geography offers a useful approach of studying individual activities and human interactions in a space-and-time context. By extending a time-geographic analytical framework, this study uses an example of arranging a face-to-face (F2F) meeting between two people to illustrate how potential F2F meeting opportunities can be impacted under four different scenarios of phone access levels. This spatiotemporal analytical framework and the various phone access scenarios are implemented in a space–time geographic information system (GIS) to demonstrate the feasibility of this analytical framework. In addition, this time-geographic framework offers analysis functions in support of quantitative assessments of ICT’s impacts on human activities.

1. Introduction

People in modern societies are increasingly experiencing the impacts of information and communication technologies (ICT), such as the Internet and mobile phones, on their daily activities and interactions with other people. The use of ICT has loosened traditional spatial–temporal constraints for people to conduct activities. For example, people with ICT can turn home or airport terminals to their workplaces, and shop at places other than brick-and-mortar stores. Researchers therefore suggest using people-based perspectives rather than traditional place-based perspectives to study human activity patterns (Miller, 2003; Kwan, 2007). Activity-based approaches, which model travels and activities at an individual-based level, highlight the advantages of people-based perspectives (McNally, 1997; Davidson et al., 2007). Moreover, collecting individual-based activity data (e.g., GPS tracking data, mobile phone tracking data) has become feasible and affordable with today’s technologies (Eagle and Pentland, 2005; González et al., 2008; Gidófalvi and Pedersen, 2009; Shaw and Yu, 2009). Developing activity-based approaches therefore has become not only more important but also more practical than before. To assess the impacts of ICT on human activity patterns, disaggregate activity-based models must take into account interactions between ICT and individual activities (Miller, 2005b). This requires a spatiotemporal analytical framework that can help articulate the mechanisms of interactions between ICT and human activities at an individual level.

Previous studies suggest that an important impact of ICT is their capabilities of increasing activity opportunity space and activity scheduling flexibility by loosening activity constraints (Mokhtarian, 1990; Kwan et al., 2007). However, limited progress has been made on assessing the impacts of ICT on activity constraints. Schwanen and Kwan (2008) measure the fixity degree of physical activities and online activities in both temporal and spatial dimensions, from which they investigate how variations in activity fixity levels are associated with the Internet usage. Although their study offers useful insights on the extent to which ICT affect individual activity constraints, its focus is not on the development of a spatiotemporal analytical environment for assessing the impacts of ICT on individual activities. There also have been studies that model potential for joint activity participation (e.g., Neutens et al., 2008; Berger et al., 2009). These studies however do not examine the effects of ICT on activity participation opportunities.

This study develops a space–time geographic information system (GIS) for studying the effects of ICT on potential activity...
opportunities at the individual person level. Since there are many possible types of influence of ICT on activity opportunities, this paper chooses the influence of various phone access scenarios on face-to-face (F2F) meeting opportunities as an example to illustrate the feasibility of assessing the impacts of ICT use on individual activity opportunities under a space-and-time context. Specifically, this paper employs the concepts of capability constraints and coupling constraints in time geography to examine the influence of various phone access scenarios on F2F meeting opportunities (Hägerstrand, 1970; Lenntorp, 1976; Forer et al., 2007). The main objectives of this study include: (1) development of a spatiotemporal analytical framework based on the time geography concepts for assessing potential F2F meeting opportunities under four different phone access scenarios and (2) implementation of the analytical framework in a space–time GIS that offers exploratory analysis functions to examine the effects of different phone access scenarios on F2F meeting opportunities. This space–time GIS analytical framework could be extended to study the influence of other forms of ICT communications (e.g., online information searches or emails) on individual activity constraints and opportunities in other studies.

The remaining sections of this paper are organized as follows. In the next section, we briefly review some key concepts of time geography and then discuss an extended time-geographic analytical framework that is capable of handling human activities and interactions in virtual space using ICT. Section 3 presents a time-geographic approach to assessing the effects of different phone access scenarios on potential F2F meeting opportunities between two people. This approach can be easily modified to accommodate meeting opportunities among multiple individuals. In the fourth section, we implement the time-geographic analytical approach in a space–time GIS with a synthetic data set to demonstrate the feasibility of the proposed approach and spatiotemporal exploratory analysis functions developed for this study. The last section offers concluding remarks and future research directions.

2. Time-geographic analytical framework

2.1. Conventional time-geographic analytical framework

Time geography, as initially developed by Hägerstrand (1970), provides a useful framework of conceptualizing and representing interactions between the agency of individuals and the space–time structures of their lives (Cloke et al., 1991). Hägerstrand (1970) identifies three types of constraints for human activities and interactions. Capability constraints are physiological necessities (e.g., sleeping, eating) and available resources (e.g., auto ownership, mobile phone ownership) that limit activity participations in space and time. Coupling constraints require an individual to occupy a specific location at a particular time in order to bundle with other individuals or entities for certain activities (e.g., F2F meeting, office hours). Authority constraints reflect general rules or laws that limit access to either spatial locations (e.g., military area) or time periods (e.g., store open hours). This study employs the concept of capability constraints for the consideration of various phone access scenarios (e.g., landline phone access only, mobile phone access) and the concept of coupling constraints for human interactions, particularly the F2F meeting opportunities discussed in this paper. In addition, the time-geographic analytical framework presented in this paper covers individual daily activity programs and access to phone communications and transportation modes, which are subject to all three types of constraints suggested in time geography.

The basic representation to connect an agency with its space–time path is a space–time path, which depicts an individual's trajectory over space and time. The shape of the trajectory of an individual is conditioned by external constraints. With individual-based tracking data, researchers can represent historical space–time paths for individuals (Kwan, 2000; Shaw et al., 2008; Yu and Shaw, 2008). Time geography also offers an analytical framework to explore potential activities conditioned by constraints. Individual activities are usually treated as fixed or flexible activities, based on their degree of flexibility in space and time. Although it is difficult to draw a distinct boundary between fixed and flexible activities, fixed activities are normally regarded as the activities that must be carried out at a fixed location and within a fixed time window, while flexible activities usually refer to the discretionary activities that can happen between two consecutive fixed activities (Miller, 1991, 2005a). A space–time prism identifies the space–time possibilities of a flexible activity between two pre-defined consecutive fixed activities (Hägerstrand, 1970; Lenntorp, 1976). In other words, we can use space–time paths to depict the location and time of fixed activities and use space–time prisms to identify the spatiotemporal extent of flexible activities.

The space–time prism approach of determining potential activity space serves as a foundation of constraints-based models for travel and activity analysis (Lenntorp, 1976; Dijst and Vidakovic, 1997; Kwan, 1997). It should be noted that the space–time prism approach focuses on identifying an individual's potential activity opportunities rather than predicting an individual's actual behaviour (Timmermans et al., 2002). This study follows this basic principle of time geography. As a result, individual preferences of choosing a particular type of opportunities over other competing opportunities (e.g., choosing a McDonald store over other fast food chain stores) is not a focus of this study. Although such individual preferences could be incorporated into the time-geographic analytical framework developed in this study. Constraints-based model built on time-geographic concepts can help researchers explore the behaviour context that is useful for developing other activity-based models such as discrete choice models and rule-based models.

2.2. Extended time-geographic analytical framework for human interactions

With respect to human interactions, Janelle (1995, 2004) suggests four types of communication modes based on their spatial–temporal characteristics in physical space and virtual space: Synchronous Presence in physical space (i.e., having a F2F meeting), Asynchronous Presence in physical space (e.g., posting a message on a bulletin board), Synchronous Tele-presence in virtual space (e.g., having a telephone conversation or an online chat), and Asynchronous Tele-presence in virtual space (e.g., sending/reading an e-mail or a text message). This study aims at analyzing how and to what extent communications via synchronous and/or asynchronous tele-presence can change the opportunities of synchronous presence.

In physical space, synchronous presence among different individuals can be identified by the overlapping segments on their space–time paths (Yu, 2006; Kang and Scott, 2008; Yu and Shaw, 2008). If we know the fixed activities of an individual, we can represent the potential activity pattern of this individual with a space–time path for his/her fixed activities and space–time prisms for his/her flexible activities that occur between the fixed activities. Miller (2005b) presents a rigorous measurement method to identify the potential synchronous presence space using interaction operations among space–time paths and space–time prisms. Neutens et al. (2007b) implement a time-geographic analysis framework to explore synchronous presence opportunities among multiple people. Neither of these studies considers the impacts of ICT communications on synchronous presence in physical space.

For the two communication modes in virtual space, Miller (2005b) also offers an analytical framework to explore potential synchronous/asynchronous tele-presence among people. When handling asynchronous tele-presence communications, it is
necessary to specify a message sender and a message receiver. An asynchronous tele-presence communication is not completed until the message receiver has an opportunity to access the communication initiated by the message sender. Miller's measurement theory for time geography therefore covers all four types of communication modes in both physical and virtual spaces (Miller, 2005b). This study extends Miller's work to analyze the potential synchronous presence opportunities due to the influence of synchronous or asynchronous tele-presence communications using telephones.

3. Potential effects of ICT on face-to-face meeting opportunities

People now can use ICT to replace F2F meetings and save trips for such meetings. They also can arrange and rearrange F2F meetings based on their changing activity schedules. Some studies suggest that ICT could enhance F2F meeting opportunities and increase the flexibility of scheduling F2F meetings (Mokhtarian and Meenakshisundaram, 1999; Eagle and Pentland, 2005; Tillema et al., 2007). Instead of studying when and why people use ICT to substitute for F2F meetings, this study focuses on examining potential F2F meeting opportunities under different phone access scenarios.

3.1. Individual activities and face-to-face meeting opportunities

Among the fixed activities, some of them take place at a fixed location and time on a regular basis. This study defines such activities as routine fixed activities. As Fig. 1a shows, a geography professor has office hours from 9:00 AM through 11:00 AM every Tuesday in her office, and teaches a transportation geography class in a particular classroom from 3:00 PM to 4:00 PM on every Tuesday. This professor sometimes may have other fixed activities that are not considered as her routine activities. For example, she receives a phone call Monday afternoon and is informed that there will be a meeting from 1:00 PM to 2:00 PM in the Dean's office the next day (Fig. 1a). Since this meeting has a fixed location and time, it also is considered a fixed activity. However, this is an occasional event that occurs only on a particular Tuesday, we name it a non-routine fixed activity. Besides the routine and non-routine fixed activities, this professor can schedule other activities during her unoccupied time windows. These activities do not have to take place at a particular time and/or location, they are called flexible activities.

In this study, we also define three types of meeting opportunities. First of all, it is possible to have a F2F meeting with other people during the period of certain fixed activities. For example, a professor can meet with students during her office hours. Such opportunities are defined as time interval meeting opportunities \( O_t \) (Fig. 1b). Other types of fixed activities (e.g., teaching a class) prevent people from having a F2F meeting at the same time. Under this circumstance, if person A does not have a prearrangement with person B but needs to see person B, person A has options of catching person B either immediately before or after person B’s fixed activity. This study calls such meeting opportunities as time spot meeting opportunities \( O_s \) (Fig. 1b). Finally, F2F meeting opportunities can be defined by a space–time prism during someone’s flexible time windows. They are known as prism meeting opportunities \( O_p \) in this study (Fig. 1b).

3.2. ICT communication modes and their space–time constraints

Among various possible ICT communication modes, this study uses phone communications as an example to illustrate the effects of ICT communications on physical activity opportunities. Specifically, we consider two types of phone devices: landline phones and mobile phones. Landline phones are tied to fixed locations (e.g., home or office); therefore, access to a landline phone is available at particular locations only. On the other hand, mobile phones allow people to stay in touch at all locations except for situations such as out of service area or out of battery power. This study examines the impacts on F2F meeting opportunities under four different scenarios of phone access levels, which include no access to phone service, landline phone service only, landline phone service for one person and mobile phone service for another person, and mobile phone service for both persons.

All phone communications involve a sender and a receiver. We define the time windows in which a person can make a phone call or send a voice/text message as send time windows \( T_s \) and the time windows in which a person can receive a phone call or access a voice/text message as receive time windows \( T_r \). When two people attempt to arrange a F2F meeting via phone communications,
they need at least one complete phone communication to confirm their arrangement. A complete phone communication is defined as a two-way information exchange, consisting of an initial information delivery from person A to person B and an information delivery from person B back to person A. For example, if two people are talking over phones, person A asks person B whether they can meet at 7 o'clock this evening. This phone communication is considered complete only after person B has responded to person A's request. If person A leaves a voice message to person B with suggested meeting time and location, this phone communication is not complete until person A receives a response from person B. Fig. 2 shows three different possible ways of completing a phone communication via synchronous and asynchronous communications. We should note that one complete phone communication does not guarantee the final arrangement of a F2F meeting. For example, people sometimes need to call each other multiple times to rearrange a meeting. Since this study is to assess all potential F2F meeting opportunities between two people, we will identify all potential F2F meeting opportunities after one complete phone communication. All subsequent phone communications to rearrange a meeting simply reduce the meeting opportunity space to a subset of its original opportunity space.

3.3. Potential face-to-face meeting opportunities

This study uses one full day (24 h) as the timeframe of analyzing potential interactions between two people. It can be adjusted to a longer period or a shorter period depending on the application needs. To illustrate how this time-geographic analytical framework works, we assume the following conditions in the example used here. First, we assume that person A needs to have a F2F meeting with person B in the day, yet person A does not have a prearrangement with person B for this meeting. Second, both persons know each other's daily routine fixed activities, but they do not know each other's actual activities unless they can communicate with each other. Therefore, person A can figure out all potential meeting opportunities with person B based on person A's knowledge of person B's routine fixed activities. However, if person B deviates from his routine fixed activities or engages in other activities during his flexible time windows, person A will not know where to find person B unless they can have a complete phone communication. Finally, we assume that they know each other's landline/mobile phone numbers.

Whether or not these two persons can have a complete phone communication plays a critical role regarding their potential F2F meeting opportunities. If both persons do not have access to phones, they can only count on their knowledge of the other person’s routine fixed activities to try to catch each other. On the other hand, if they have access to either landline phones or mobile phones, it becomes feasible for them to communicate with each other. Mobile phones clearly offer a higher level of spatial and temporal flexibility than landline phones to reach other people or be reached by other people. This paper shows how we can assess all potential F2F meeting opportunities between two people when they complete a phone communication. Since our focus is on finding the maximum possible potential meeting opportunities, the earliest possible time of completing a phone communication \(t_c\) therefore serves as an important parameter in the analytical framework presented in this paper.

In the following sections, we will first present an approach of calculating \(t_c\) for each type of a complete phone communication (Fig. 2). Then we will present an approach of analyzing potential F2F meeting opportunities before and after a complete phone communication. Before calculating \(t_c\), we need to define the send time windows and the receive time windows for each person:

\[
T^A_s = \bigcup_{i=1} \left[ (t^A_{s\text{,start}}, t^A_{s\text{,end}}) \right], \quad i \in \mathbb{N}^+
\]

\[
T^B_r = \bigcup_{j=1} \left[ (t^B_{r\text{,start}}, t^B_{r\text{,end}}) \right], \quad j \in \mathbb{N}^+
\]

\[
T^A_r = \bigcup_{k=1} \left[ (t^A_{r\text{,start}}, t^A_{r\text{,end}}) \right], \quad k \in \mathbb{N}^+
\]

\[
T^B_s = \bigcup_{l=1} \left[ (t^B_{s\text{,start}}, t^B_{s\text{,end}}) \right], \quad l \in \mathbb{N}^+
\]

where

- \(i, j, k, l\) are indices;
- \(T^A_s\) is the set of send time windows of person A;
- \(T^A_r\) is the set of receive time windows of person A;
- \(T^B_r\) is the set of send time windows of person B;
- \(T^B_s\) is the set of receive time windows of person B;
- \(\{ (t^A_{s\text{,start}}, t^A_{s\text{,end}}) \} \) are the start time and end time in each send time window for person A;
- \(\{ (t^A_{r\text{,start}}, t^A_{r\text{,end}}) \} \) are the start time and end time in each receive time window for person A;
- \(\{ (t^B_{s\text{,start}}, t^B_{s\text{,end}}) \} \) are the start time and end time in each send time window for person B;
- \(\{ (t^B_{r\text{,start}}, t^B_{r\text{,end}}) \} \) are the start time and end time in each receive time window for person B.

3.3.1. Synchronous phone communication

For the first type of phone communication (Fig. 2a), the method of finding the earliest time to finish a synchronous phone communication between person A and person B \(t_c\) is described below (Fig. 3a):

![Fig. 2. Three modes of a complete phone communication.](image-url)
• Step 1: Calculate the intersection of the set of send time windows for person A and the set of receive time windows for person B:
\[ T_{A}^{S} \cap T_{B}^{R} \neq \emptyset \]
then
\[ T_{A}^{S} \cap T_{B}^{R} = \bigcup_{m=1}^{M} \{(t_{\text{start}}^{m}, t_{\text{end}}^{m})\}, \quad m \in \mathbb{N}^{+} \]  
where
- \( m \) is an index;
- \( \{(t_{\text{start}}^{m}, t_{\text{end}}^{m})\} \) indicates the start time and the end time in each time window when person A can call person B.

- Step 2: Calculate \( t_{c1} \):
\[ t_{c1} = \min((t_{\text{start}}^{m})) \]  
where
- \( \min((t_{\text{start}}^{m})) \) finds the earliest start time in all time windows when person A can call person B.

3.3.2. Asynchronous message communication

For the second type of phone communication (Fig. 2b), the procedure of finding the earliest time to finish an asynchronous message communication between person A and person B (\( t_{c2} \)) is given below (Fig. 3b):

- Step 1: Identify the first send time window for person A (\( T_{A}^{S}_{1} \)).
- Step 2: Find the earliest receive time window (\( T_{B}^{R}_{k} \)) when person B can receive the message sent from person A.
- Step 3: Find the earliest send time window (\( T_{A}^{S}_{k} \)) when person B can send a message back to person A.
- Step 4: Find the earliest receive time window (\( T_{A}^{R}_{k} \)) when person A can receive the feedback message sent from person B.
- Step 5: Calculate \( t_{c2} \):
\[ t_{c2} = (t_{\text{start}}^{k}) \]  
where
- \( (t_{\text{start}}^{k}) \) is the start time in the earliest receive time window (\( T_{A}^{R}_{k} \)) when person A can receive the feedback message sent from person B.

3.3.3. Asynchronous mixed communication

For the third type of phone communication (Fig. 2c), the procedure of finding the earliest time to finish an asynchronous mixed communication between person A and person B (\( t_{c3} \)) is described below (Fig. 3c):

- Step 1: Identify the first send time window for person A (\( T_{A}^{S}_{1} \)).
- Step 2: Find the earliest receive time window (\( T_{B}^{R}_{k} \)) when person B can receive the message sent from person A.
- Step 3: Find the earliest send time window (\( T_{A}^{S}_{k} \)) when person B can send a message back to person A.
- Step 4: Calculate the intersection set of (\( T_{A}^{R}_{k} \)) and the set of receive time windows for person A.

if \( T_{A}^{S}_{k} \cap T_{A}^{R}_{k} \neq \emptyset \)
then
\[ T_{A}^{S}_{k} \cap T_{A}^{R}_{k} = (t_{\text{start}}^{k}, t_{\text{end}}^{k}) \]  
where
- \( (t_{\text{start}}^{k}, t_{\text{end}}^{k}) \) indicates the start time and the end time in the earliest time window when person B can call person A after person B receives the message from person A.
- Step 5: Calculate \( t_{c3} \):
\[ t_{c3} = t_{\text{end}}^{k} \]  
Finally, the earliest time of finishing a complete phone communication between two persons (\( t_{c} \)) is:
\[ t_{c} = \min\{t_{c1}, t_{c2}, t_{c3}\} \]  
(10)

3.3.4. Potential F2F meeting opportunities

In the case that person A wants to meet with person B without phone access, person A must rely on her knowledge of person B’s routine fixed activities to find person B. In other words, only the time interval meeting opportunities and time spot meeting opportunities based on person B’s routine fixed activities are perceived by person A as potential meeting opportunities. Even though there may be available prism meeting opportunities during their flexible time windows, person A cannot take advantage of such opportunities because they cannot communicate with each other. If person B changes his routine fixed activities, their F2F meeting opportunities may further shrink. Therefore, the potential F2F meeting opportunities \( O_{(t_{c1})} \) between person A and person B for the study period (\( t > 0 \)) when they do not have phone access are defined as follows:
\[ O_{(t_{c1})} = O_{(t_{c1})}^{A} \cap O_{(t_{c1})}^{B} \]  
(11)
where
- \( O_{(t_{c1})}^{A} \) is person A’s full meeting opportunity set;
- \( O_{(t_{c1})}^{B} \) is person B’s full meeting opportunity set perceived by person A;
- \( O_{(t_{c1})}^{A} \) is person B’s time spot meeting opportunity set perceived by person A;
- \( O_{(t_{c1})}^{B} \) is person B’s time interval meeting opportunity set perceived by person A.

If persons A and B can finish a complete phone communication, they then will know all feasible F2F meeting opportunities after \( t_{c} \) (\( t > t_{c} \)). In this situation, their potential F2F meeting opportunity set becomes the intersection of their respective potential meeting opportunity sets modified by their actual activities. Compared with the potential meeting opportunities perceived by person A before the time they completed a phone communication (\( t_{c} \)), the potential meeting opportunity set now includes the meeting opportunities based on not only person B’s routine fixed activities but also his non-routine fixed activities that could not be known without a complete phone communication. In addition, they could arrange a F2F meeting in the prism meeting opportunity set. Their potential F2F meeting opportunities \( O_{(t_{c1})} \) is:
\[ \tilde{O}_{(t_{c1})} = O_{(t_{c1})}^{A} \cap O_{(t_{c1})}^{B} \]  
(12)
where
- \( O_{(t_{c1})}^{A} \) is person A’s full meeting opportunity set;
- \( O_{(t_{c1})}^{B} \) is person B’s full meeting opportunity set;
- \( O_{p} \) is person B’s prism meeting opportunity set.

Finally the potential F2F meeting opportunities for person A and person B \( O_{(t_{c1})} \) is:
\[ O_{(t_{c1})} = \tilde{O}_{(t_{c1})} \cap O_{(t_{c1})}^{B} \]  
(13)

3.4. Scenario analysis

The above analysis framework is used to explore the impacts of phone communication modes on F2F meeting opportunities under the following four scenarios: (1) neither person has phone access during the day; (2) neither person carries a mobile phone, but both people have access to landline phones; (3) person A carries a
mobile phone, but person B has access to landline phones only; and (4) both persons carry a mobile phone.

The first scenario is a benchmark case that assumes both persons do not have access to either landline or mobile phones at all. This benchmark scenario allows us to evaluate how different levels of phone access affect a person’s F2F meeting opportunities. Fig. 4a1 shows the actual space–time paths of person A and person B. In addition, the space–time prisms around person A’s space–time path represent person A’s potential spatiotemporal extents of having a F2F meeting with person B. Since neither person has phone access, person A has no way of knowing that person B stays longer at the lab than he usually does. As a result, person A cannot perceive the additional time interval meeting opportunity with person B in the afternoon that becomes feasible because of person B’s non-routine extended stay at the lab. In this case, the only F2F meeting opportunity with B that can be perceived by person A is the time interval meeting opportunity window in the morning (Fig. 4a2).

In the second scenario (Fig. 4b1), both person A and person B have access to landline phones at particular locations (e.g. home, office, lab). Before person A leaves home in the morning, she can leave a voice message on person B’s landline phone. When person B returns a phone call during the time window $t_{R1}$, person A is out of her home. The earliest possible time that person A can receive the message left by person B therefore is at $T_{S1}^B$ (i.e., the earliest time they can finish a complete asynchronous message communication, $t_c$). Since it now is feasible for persons A to learn from person B that person B intends to stay longer at the lab, the time interval meeting opportunity window in the afternoon becomes a feasible option for them to have a F2F meeting in addition to the meeting opportunity in the morning (Fig. 4b2).

The third scenario assumes that person A has a mobile phone while person B can only access landline phones at his office and lab. Once person B arrives at his office, person A can reach person B via phone. As a result, the start time of $T_{S1}^R$ is the earliest possible time for person A to communicate with person B’s to make meeting arrangements (i.e. $t_c$ in Fig. 4c1). In this case, it is feasible for person A to know all possible F2F meeting opportunities after $t_c$, including two time interval meeting opportunity windows and a prism meeting opportunity window around noon (Fig. 4c2).

In the fourth scenario (Fig. 4d1), both persons carry a mobile phone, but person B does not turn on his mobile phone until 11 AM when he walks out his office. Furthermore, we assume that person A does not know person B’s work phone number. In this case, 11 AM is the earliest possible time for them to communicate and stay in touch (i.e., $t_c$ in Fig. 4d1). Again, they can meet at any of the two time interval opportunity windows and/or in the prism time opportunity window (Fig. 4d2).

The above four scenarios demonstrate the capability of proposed analysis framework to explicitly evaluate the effects of different phone communication modes on potential F2F meeting opportunities. In addition, this analysis framework can assist researchers to quantitatively assess the spatial and temporal extents on F2F meeting opportunities due to different phone communication access scenarios.

4. A space–time GIS prototype

4.1. Space–time GIS design and implementation

There have been a number of studies with GIS implementations of space–time paths and space–time prisms (e.g., Miller, 1991; Kwan, 2000, 2004; Buliung and Kanaroglou, 2006; Yu, 2006; Neutens et al., 2007b; Shaw et al., 2008; Yu and Shaw, 2008; Miller and Bridwell, 2009; Shaw and Yu, 2009). Although these studies have made significant progress on GIS implementation of time geography concepts, they have not explicitly considered the impacts of communication modes on human interaction opportunities. This study builds on and extends the space–time GIS prototype system of Shaw and Yu (2009) to assess the influence of different phone access levels on F2F meeting opportunities.

Based on a temporal dynamic segmentation design in the 3D environment of ArcScene (Environmental Systems Research Institute, Redland, CA), this prototype system uses the $x$ and $y$ dimensions for spatial representation, and the $z$ dimension for temporal representation. A space–time path is visualized as a 3D polyline. A space–time prism is represented with a set of vertical 3D polylines extruded from the transportation network junctions that are accessible under spatial–temporal constraints (see Yu and Shaw (2008) for details). The potential F2F meeting places within a space–time prism are represented by transportation network junctions, which are used as surrogates for real points of interests in this study. Time spot meeting opportunities appear in pairs,
defined as two 5-min windows before and after a fixed activity. A time interval meeting opportunity is a vertical line whose length is determined by the time period of a fixed activity. A prism meeting opportunity is created by a space–time prism, which consists of a set of vertical lines, whose lengths represent the maximum available activity time at each network location. Potential F2F meeting opportunities between two or more persons can be evaluated by checking if their potential meeting opportunities overlap.
4.2. A case study

This study selects Knox County, Tennessee as an example to illustrate a space–time GIS implementation of the proposed analytical framework. Three alternative travel modes (private automobile, bus, and walk) are considered in this implementation. Average travel speeds for these three modes are estimated and assigned to network links. Bus routes and the street network are
connected at the bus stops. This case study compares the impacts of different phone communication modes on F2F meeting opportunity space for three pairs of people who have different activity patterns and use different transportation modes. Table 1 lists their home locations, primary travel modes, and major activities on a particular day. To reveal the impacts of different phone communication modes, this case study illustrates two extreme situations of phone accessibility: no phone access at all versus full-day mobile phone access. The potential F2F meeting opportunities without phone access and with mobile phone access are computed for each pair of the three persons. A minimum F2F meeting time (20 min) and a maximum travel time for a single trip (30 min) are used in this case study. Users of this space–time GIS analysis environment can set their own parameter values via a user interface (Fig. 5). Custom functions of “Explore Person A” and “Explore Person B” analyze and represent each person’s own potential F2F meeting opportunities. The “Explore Meeting Opportunities” function computes and displays the potential F2F meeting opportunities between each pair of persons, including when person A can meet person B and vice versa.

Fig. 6 shows the analysis results for each pair of these three persons and the visualization function provided by this prototype system. The minimum meeting time of 20 min excludes time spot meeting opportunities. Because person A can only take a bus or walk, her space–time prisms are not continuous but clustered around two accessible bus stops. In addition, due to the settings of minimum meeting time, maximum travel time, mixed travel modes, and travel speeds, the actual space–time prisms have different shapes from the theoretical shape of two joined cones suggested in time geography. Without phone access, person A and person B only have one potential meeting opportunity (Fig. 6a2). When person B works in the office in the morning, person A can visit person B since person A knows person B’s routine fixed activity and person A has free time in the morning. When they both

<table>
<thead>
<tr>
<th>Activity</th>
<th>Home location</th>
<th>Travel mode</th>
<th>Activity</th>
<th>Home location</th>
<th>Travel mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:38–9:05 Taking a bus to UT (RF, N)</td>
<td>Near UT campus</td>
<td>Bus</td>
<td>7:25–8:05 Driving a car to office (RF, N)</td>
<td>In East Knox</td>
<td>Car</td>
</tr>
<tr>
<td>9:15–10:20 Taking a class at UT (RF, N)</td>
<td></td>
<td></td>
<td>8:05–9:20 Working in office (RF, Y)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10:30–12:00 Studying in library</td>
<td></td>
<td></td>
<td>9:45–10:30 Having a meeting at UT (NonRF, N)</td>
<td>In West Knox</td>
<td>Car</td>
</tr>
<tr>
<td>12:20–13:20 Having a meeting (NonRF, N)</td>
<td></td>
<td></td>
<td>10:30–12:30 Working in office (RF, Y)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13:35–14:30 Studying at lab A</td>
<td></td>
<td></td>
<td>12:20–12:40 Having lunch at downtown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14:30–17:00 Having lab hours (RF, Y)</td>
<td></td>
<td></td>
<td>13:00–16:00 Taking a class at UT (RF, N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17:10–20:00 Studying at Starbucks</td>
<td></td>
<td></td>
<td>16:30–18:00 Working out at gym (RF, N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20:10–20:30 Taking a bus home</td>
<td></td>
<td></td>
<td>18:00–18:20 Driving car home (RF, N)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(RF and NonRF refer to routine fixed activities and non-routine fixed activities. Y and N refer to activities in which people can and cannot meet with others. Activities without any of the four notations are flexible activities.)

Fig. 5. The 3D spatial–temporal analysis environment of the space–time GIS prototype.
have access to a mobile phone, Fig. 6a3 indicates that they do not gain additional F2F potential meeting opportunities with mobile phone access. This example illustrates that improved ICT access does not always guarantee more meeting opportunities due to other constraints on human activities (e.g., one person has flexible time while the other person is engaged in a fixed activity such as the case shown in Fig. 6a1).

The second example (i.e., meeting opportunities between person A and person C) shows that mobile phone access can relax some spatiotemporal constraints and increase potential F2F meeting opportunities. In this case, person A does not own a car and therefore cannot reach person C’s office by bus during person A’s 2-h flexible time window in the morning. As a result, it is not possible for person A to meet person C if person A only relies on his knowledge of person C’s fixed routine activities and does not have a phone communication with person C for updates. On the other hand, person C knows that person A has lab hours in the afternoon and person C happens to have free time in the afternoon. This offers a potential meeting opportunity (Fig. 6b2). The prototype system reports the number of potential meeting opportunities, the maximum potential meeting time, and the minimum travel time for each potential meeting location. The length of the 3D space-time path segments shown in grey colour represents the maximum F2F meeting time window (Fig. 6b3). Without phone access, the maximum meeting time for this meeting opportunity is 35 min, and person C needs to drive 25 min to reach the meeting place. With mobile phone access, they can arrange a F2F meeting during their lunch time or after work when they have more free time. The maximum meeting time therefore increases to one and a half hours, and the total minimum travel time for both of them is only 25 min.

The example between person B and person C is an extreme case. They both have high mobility with a car and some flexible time windows. They are also in close spatial proximity during certain time periods in the day. However, their activity schedules constrained by their fixed activities are not compatible with each other. Regardless of their mobile phone accessibility, they do not have any potential F2F meeting opportunities.

The above examples demonstrate different effects of phone communication modes on potential F2F meeting opportunities.
for different people. As mobile phones become widely used in today’s society, they certainly have greatly enhanced our opportunities of staying in touch. However, increased opportunities of staying in touch do not necessarily translate into increased opportunities of having more F2F interaction opportunities in the physical world as indicated by the examples above. Previous research suggests that F2F meetings diminish with an increase in geographical distance between the contact members (Boase et al., 2006; Tølling et al., 2007). These studies often consider only distance variables (e.g., distance between the home locations of contact persons) and leave out temporal constraints (e.g., the available time windows for meetings) and spatial context (e.g., feasible meeting locations between two people.) The prototype space–time GIS developed in this study can help researchers systematically explore these spatial–temporal contexts and constraints to better understand the interactions between communications in virtual space (e.g., phone communications or Internet communications) and activities in physical space (e.g., F2F meetings or shopping behaviour).

With the representation of potential F2F meeting opportunities in space and time, this prototype system can also suggest the activity space for potential interactions between individuals under various constraints. Taking person A and person C as an example, they will face significantly stronger coupling constraints when they have no access to phones, compared with the case that they have access to mobile phones. Those grey 3D space–time paths in Fig. 6b2 and b3 reveal the difference of the potential meeting opportunities between the two individuals under the two scenarios. In other words, given their general routine activities, if they want to arrange a F2F meeting, the opportunity will be more limited in space and time when having no access to phones comparing with the case of having mobile phones. Such explicit spatial–temporal modelling approach to an individual’s potential activity space could be useful for developing individual accessibility measurements and activity-based models in the age of instant information access.

5. Conclusions

Information and communication technologies (ICT) have been reported to cause changes to human activity and interaction patterns, which in turn create effects on travel patterns, urban forms, and social networks. Although a number of studies have been conducted to identify and analyze ICT impacts on individual activities, most of these studies do not offer an analytical framework that can systematically evaluate the interactions between ICT and individual activity constraints in a space-and-time context to help researchers assess the impacts of ICT on individual activities. This study extends the time-geographic analytical framework to quantitatively assess the impacts of phone usage on potential F2F meeting opportunities. To analyze the interactions between phone communication and F2F meeting opportunities, we develop a method to calculate the potential earliest time of finishing a complete phone communication between two people. Since meeting opportunities could be updated during a phone communication, we compute the potential F2F meeting opportunity sets before and after the potential earliest complete phone communication separately. These two meeting opportunity sets then form a complete set of all potential F2F meeting opportunities. This analytical framework offers a useful approach for activity-based models to incorporate ICT impacts. With the capability of comparing activity opportunity spaces for people who have access to ICT versus those who do not, this analytical framework also has potential of making contributions to studies of “digital divide” among different population groups.

This paper presents an initial analytical framework for studying complex interactions between ICT and human activities with a space-and-time approach. There are a number of possible enhancements and extensions to this initial analytical framework. First of all, this analytical framework can be extended to explore F2F meeting opportunities among multiple persons (Neutens et al., 2008) and explicitly consider multipurpose trips (Soo et al., 2009). In addition, this framework can be extended to study other ICT alternatives (e.g., Internet communications via computers, mobile phones, or other mobile devices). We could, for example, examine the differences in shopping opportunities among people who have Internet access versus those who do not. Furthermore, this study introduces a concept of non-routine fixed activities to capture activities that deviate from an individual’s daily activity routine. This concept suggests a need of rearranging individual activities under a dynamic environment. Forer et al. (2007) present a conceptual time-geographic analysis framework to reflect the dynamic process of (re)arranging individual activities with the use of ICT. The analytical framework presented in this study could incorporate other modelling approaches such as decision-making rules, probability functions, or simulation models to address the dynamic process of arranging a F2F meeting.

In today’s ICT world, researchers also suggest that the concept of fixed activities has become blurred (Schwane and Kwan, 2008). Human activities tend to become more segmented and spontaneous under the additional spatiotemporal flexibilities enabled by ICT (Couclelis, 2004; Shaw and Yu, 2005). We therefore will be better to introduce various flexibility levels instead of using a binary definition of fixed versus flexible activities to represent individual activities in the analytical framework. The work of Neutens et al. (2007a) and Kuijpers et al. (2010) provide useful information to pursue this research direction. Finally, the design of this analytical framework can be enhanced with real world data collected from empirical studies. Recent studies have demonstrated that it is feasible to collect individual trajectories and phone communication records (Eagle and Pentland, 2005; Licoppe et al., 2008). Incorporating such datasets into the analytical framework presented in this study will not only allow us to test and improve the analytical framework but also provide empirical data for researchers to gain insight into the interactions between communications in virtual space and human activities in physical space.

Acknowledgements

This research is supported by US National Science Foundation Grant No. BCS-0616724. The authors would like to thank the anonymous reviewers for their helpful comments.

References


