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Accepted author version posted online: 27 Apr 2012.Published
online: 09 May 2012.

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A Parasitic Model is proposed in this study for Digital Earth running on mobile phones through a mobile network. Because of mobile phones' limited capabilities in high-performance computing, rendering, storing, and networking (CRSN), these functions are accomplished by a superior host computer in this model. Rendered virtual scenes are compressed in a time-series as a data stream and are sent to the mobile phone through a mobile network, thus allowing Digital Earth to be operated on a mobile phone. This study examines a prototype and shows that a Mobile Digital Earth based on a Parasitic Model can achieve functionality beyond the mobile phone's actual hardware capabilities and can reduce network traffic. These results demonstrate quasi-real-time interactions, but with bandwidth increases in next-generation mobile networks such as 4G and 5G, there is potential for real-time interactions in the near future.

Keywords: Parasitic Model; Mobile Digital Earth; adaptive transfer strategy; mobile phone; mobile network

1. Introduction

Recent years have seen great advances in the Digital Earth concept since the vision was first articulated by Gore (1998). Digital Earth has profoundly impacted scientific research, commercial applications, and human life. Research areas, including digital continents (Georgiadou *et al.* 2011), digital nations (Wu and Tong 2008), digital cities (Zhu and Hu 2010), and digital oceans (Zhang *et al.* 2011), have been derived from the metaphor of Digital Earth and have been evolving at different geo-scales. Companies such as Google and Microsoft have made the Digital Earth experience familiar to hundreds of millions of users worldwide through their geo-browsers (Annoni *et al.* 2011). To date, human life has already been affected by Digital Earth (Butler 2006).

Craglia *et al.* (2008), Goodchild (2008), and Grossner *et al.* (2008) have recently considered the extent to which Gore's original vision has been achieved (Craglia *et al.* 2012). New revised visions of Digital Earth have been proposed (Annoni *et al.* 2011, Georgiadou *et al.* 2011, Craglia *et al.* 2012). An aspect of the European perspective (Annoni *et al.* 2011) is that Digital Earth could be an 'observation web'

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with human-centered sensing and citizen-contributed information. The opinion is supported by the African vision; Georgiadou *et al.* (2011) argued that Digital Earth can act as a 'participatory sensing' platform, called the 'human sensor web', so that local information resources can be collected by citizens to monitor, measure, and forecast. Craglia *et al.* (2012) envisioned a blueprint of Digital Earth for the next decade: in 2020, people can operate Digital Earth personally or professionally throughout their daily lives and can communicate with their friends or share their individual information using Digital Earth. One feasible approach for the above visions is to make Digital Earth portable to be accessible to people at all times so that it can be operated to collect and share information at any time and at any place. However, most current Digital Earth applications cannot meet those demands because they are based on non-mobile Internet connections and personal computers.

The mobile network, like the Internet, has evolved into a dominant communication network, and mobile subscribers have increased substantially every year. Morgan Stanley (2009) stated that we are 'now in [the] early innings of [a] mobile Internet cycle, the 5th cycle of [the] last half century', and 'regarding pace of change, we believe more users will likely connect to the Internet via mobile phones than desktop PCs within 5 years'. At the end of 2010, there were 5.28 billion mobile subscribers, compared with a global population of 6.8 billion.[1] In China, the number of mobile subscribers reached 9.4 billion at the end of August 2011, and the number of mobile network users will reach 4.15 billion by the end of 2011, which is nearly 1.0 billion more than that at the end of 2010.[2]

A recent trend is the combination of Digital Earth and mobile technology for a new application – Mobile Digital Earth (MDE). In fact, as a leader of Digital Earth research and applications, Google has made great efforts to directly transplant its computer and Internet-based Google Earth to mobile devices, for example, Google Earth running on Nexus One, Droid, iPhone, iPad and iPodTouch, and other mobile platforms.[3] However, the target mobile operating system, the instruction set of central processing units (CPUs), and the programming languages differ, as do the hardware. The only option is to re-program Digital Earth for each mobile platform and to maintain and update various versions for the same functions. Moreover, the computing and rendering of 3D virtual scenes will be local and rely strongly on the hardware capabilities of mobile devices. The lower the capability is, the poorer the user experience will be.

The advantages and disadvantages of mobile technology are as follows. The main advantages are portability and pervasiveness. Because the signal coverage of a mobile network is spatially 3D and the mobile terminals are smaller and lighter than a computer, mobile terminals can send and receive data at any location (such as on mountains or at sea), at any time, and in any state of motion (static or moving).

However, the disadvantages of mobile technology are also significant, especially when applied to Digital Earth. Digital Earth is usually expected to consist of 3D virtual scenes, which may display a variety of mass materials and objects captured in digital elevation models (DEMs), remote sensing images, or other complex geographic process models such as those for clouds and different types of precipitation. However, most mobile phones have clearly inferior computing, rendering, and storage abilities compared with personal computers. Furthermore, Digital Earth on a mobile device must fetch massive amounts of geographic source data through a mobile network to build a virtual scene, which places tremendous pressure on the low-bandwidth mobile

network. Weaknesses in computing, rendering, storing, and networking (CRSN) are obstacles for any approach involving directly copying Digital Earth's mode of operation from personal computers to mobile platforms. Some features that run on personal computers cannot run on mobile platforms; for example, the 3D buildings in Google Earth for mobile can only be displayed on specific devices, such as a Motorola Xoom with a dual-core CPU. Other advanced features such as ocean and sunlight are not yet supported by mobile phones,[4] which degrades the user experience. Thus, this approach to bringing Digital Earth to mobile phones has bottlenecks.

Because there are few research papers on MDE, a new approach should be studied to overcome the CRSN obstacles listed above to enable running a fluent and scalable MDE on mobile phones through mobile networks.

2. The Parasitic Model

The process of rendering Digital Earth on a personal computer comprises the following five stages: (1) detecting the virtual scene's status changes; (2) fetching geographic source data through the network; (3) caching these data in memory; (4) rendering the original geographic data into a frame buffer; and (5) drawing the frame buffer on the screen.

Because mobile phones have bottlenecks in CRSN that prevent them from meeting the needs of Digital Earth rendering, will it be feasible to transfer CRSN tasks to other devices with superior performance to achieve smooth and intuitive use of Digital Earth on mobile phones?

This idea can be called a 'Parasitic Model'. Parasitic models employ superior devices, rather than mobile phones, to accomplish CRSN tasks. Then the results are sent back to the mobile phone. In this model, the mobile phones are only the input and output interface. Although the actual work is performed by the superior devices, the mobile phone seems to accomplish the processing. The superior devices can thus be figuratively viewed as the biological 'host' and the mobile phones as the 'parasites'. Typical hosts are computers or computer clusters, which are significantly superior to mobile phones in CRSN. The combination of the 'host' and the 'parasite' takes advantage of both entities' strengths.

Mobile Digital Earth based on the Parasitic Model, which uses the computer as the host and the network as the carrier, is feasible (see Figure 1). The workflow can

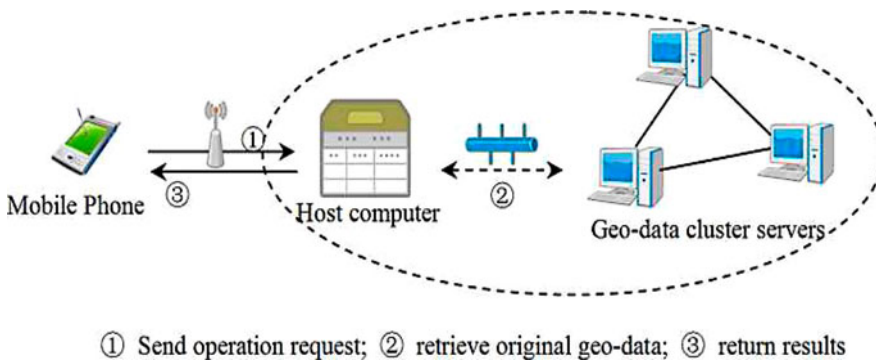① Send operation request; ② retrieve original geo-data; ③ return results

Figure 1. Framework of the Parasitic Model.

be described as follows. The mobile phone receives the user's input, which is sent through the mobile network to the host computer. The host computer then fetches geographic source data, including terrain, remote-sensing images, and other digital models, through a broadband Internet connection. These original data are then rendered into buffered images, the result of the 3D virtual scene, employing powerful CPU/Graphic processing unit (GPU) or other high-performance computing units. The resulting buffered images are compressed and sent back to mobile phones through the mobile network. The mobile phone then displays the images as Digital Earth.

3. Key technologies

3.1. Strategy for compressing virtual scene results into a data stream

A classic strategy in WebGIS is based on the thin-client mode. To reduce the storage, computation, and rendering pressures of the client, all data are rendered into a series of buffered images on the server in advance, and the images are transmitted through the network. Because WebGIS has a fixed viewing angle, which is always a bird's-eye view, the level of detail can be preconditioned according to special scale intervals. However, because Digital Earth is always 3D and the viewing angle, the viewpoint, and the path cannot be predetermined, no images can be pre-rendered and buffered on the server for distribution. The image-based strategy of traditional WebGIS does not accommodate the needs of MDE.

In light of this, the characteristics of user operation in the 3D virtual scenes of Digital Earth should be examined. Users' continuous operations in Digital Earth will generate a series of consecutive virtual scenes that always partially overlap. Thus, the results can be regarded as time-series image sequences with duplicated data. Because these duplicated data have little effect on scene reconstruction for the user's interactions, these data should be eliminated so that fewer data are transferred through the network. Effective data compression strategies should be introduced to reduce the time spent on data transfer and improve real-time responses to user operations.

A method using streaming media was chosen in this study to transfer data because of its high compression ratio for time-series images. In the streaming media strategy, buffered images rendered from the geographic source data by the host computer are encoded into streaming data according to a specific coding protocol. The duplicated data between two sequential images are then eliminated by the coding algorithm. The streaming data are then sent to the mobile phone through the mobile network. When the mobile phones receive the data stream, it is decoded and recovered into buffered images of the virtual scene for final display. MPEG-4, H.264, and other streaming media algorithms can be used as the data carrier.

3.2. Adaptive transfer strategy for a low-bandwidth mobile network

3.2.1. Accumulated delay on a low-bandwidth network

Another key aspect of MDE based on the Parasitic Model is the transfer of compressed, streaming data from the host computer to mobile phones through a mobile network. The data transfer speed should closely correspond with both the network capacity and the performances of the target mobile phones. In Figure 2, let

Figure 2. Process map of the adaptive transfer strategy.

the data encoding time at the host computer be ΔT_4; the submitting time to the network be ΔT; the duration of data transfer on the network from the host computer to the mobile phone be ΔT_1; and the total time including receiving, decoding, and displaying the data on the mobile phone be ΔT_2. The traditional approach is to submit data generated on the host computer to the network and broadcast these data at a specific interval. Because the submitting interval is always fixed, some consequences will result. First, when $(\Delta T_4 + \Delta T) > (\Delta T_1 + \Delta T_2)$, the encoded virtual scenes will be queued, waiting to be submitted. The queued data will accumulate increasingly over time, which means that the virtual scene results cannot be received by the mobile phone in a timely manner, causing delays between the user's operations and the display of the operation results. In addition, the delays will accumulate over time, and interaction consistency would not be guaranteed. Second, when $(\Delta T_4 + \Delta T) < (\Delta T_1 + \Delta T_2)$, the network's bandwidth and the mobile phone's performance capabilities will not be fully utilized to achieve the best interactions.

3.2.2. Adaptive transfer strategy considering network capacity and mobile phone performance

An adaptive transfer strategy, based on feedback, is proposed to achieve consistency between the submission speed and the network capacity and performance of target mobile phones. The mechanism is that, after specific intervals, which can be simply viewed as N frames, the mobile terminal should send fixed feedback data to the host computer over m frames from frame $N + 1$ to frame $N + m$. Based on these m feedback frames, the host computer will then calculate the total time T spent on the network and on the mobile phone displays. The average time T_a can then be obtained by T/m. The time T_a will be the time interval between two sequential data-submission operations to the network for the next N frames. During the next N frames, no other feedback will be sent to the host computer. Thus, the submission speed at the host computer will be kept consistent with the network speed and the mobile phone's display performance. Because the interval calculation repeats every N frames, the consistency is dynamic, with a small amount of fluctuation over time.

The algorithm to obtain T_a is as follows:

In Figure 2, let the moment when the result data are submitted to the network by the host computer be T_1. The moment when the host computer receives the feedback

from the mobile phone is T_2, and the transfer time for the feedback data on the network is ΔT_3. We then have the following:

$$T_2 - T_1 = \Delta T_1 + \Delta T_2 + \Delta T_3 \tag{1}$$

where $\Delta T_1 + \Delta T_2$ is the time to be solved. Because T_1 and T_2 can be obtained, the only required value is ΔT_3. To calculate ΔT_3, it is assumed that the time spent on the network is equal when transferring the same data twice in rapid succession. The moment when the host computer receives the feedback message is recorded as T_2, and the message is sent back to the mobile phone and then returned to the host computer again. The moment when the message is sent back from the host computer is recorded as T_3, and the moment when the returned message is received at the host computer is recorded as T_4. ΔT_3 can then be approximated as:

$$T_4 - T_3 = \Delta T_3 \times 2 \tag{2}$$

Because the average data encoding time over m frames at the host computer can be calculated as:

$$\overline{\Delta T_4} = \frac{1}{m} \sum_{i=1}^{m} \Delta T_4, \tag{3}$$

the average interval T_a for the following N frames can be determined using the following:

$$T_a + \overline{\Delta T_4} = \overline{\Delta T_1} + \overline{\Delta T_2} = \frac{1}{m} \sum_{i=1}^{m} [(T_2 - T_1) - (T_4 - T_3)/2] \tag{4}$$

$$T_a = \frac{1}{m} \sum_{i=1}^{m} [(T_2 - T_1) - (T_4 - T_3)/2 - \Delta T_4] \tag{5}$$

3.3. A semantic-mapper model to supplement the mobile phone's HCI

The human–computer interface (HCI) of personal computers is different from mobile phone HCIs. For example, a personal computer's mouse actions may be click, double-click, right-click, middle-click, wheel scroll, drag, right-drag, and so on. It is difficult for mobile phones to accomplish such actions because there is no input peripheral such as a mouse but a stylus for which the main manipulation is based on a single touch or 'click'. Thus, another key issue is the realization of the corresponding HCIs on mobile phones to achieve the full functionality of Digital Earth as though it were running on a personal computer.

For this study, all of the interactions on the mobile phone are abstracted to an interaction type, semantic mark bit, and variable-length parameters (Figure 3). The interaction type refers to the user's original operation, for example, the 'click' operation. The mark bit is the mapper from the original operation to different meanings; for example, when the mark is 2, the original click is mapped as a right-click and when it is 3, the original click is mapped as a double-click. The variable-length parameters are the operation contents, such as the position for a click or right-click and the start and end positions for a drag.
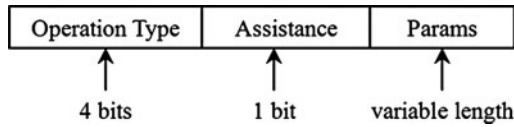
Operation Type	Assistance	Params

4 bits   1 bit   variable length

Figure 3. Coding format of a user's interactions.

Length of the package			
Data length A	Operation A	Assistance a	Params A
Data length B	Operation B	Assistance b	Params B
Data length N	Operation N	Assistance n	Params C
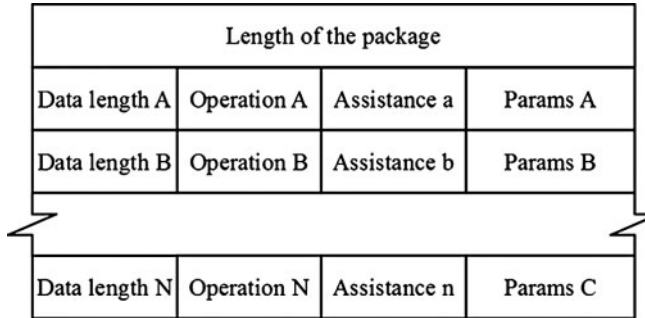
Figure 4. Package format of encoded operations.

All of the user's interactions are packaged into an integrated buffer (Figure 4), which will be sent to the host computer, and when the host computer receives the buffer, the user's original interactions are translated into the actual operations according to the semantic mark protocols to modify the status of the Digital Earth service on the host computer. Theoretically, all of the HCI operations of a computer can thus be simulated on a mobile phone by the semantic mapper model.

4. The MDE prototype

Based on the Parasitic Model and key technologies mentioned above, an MDE prototype was constructed for this study. The server program on the host computer was implemented in C++, and the host computer was running Windows XP SP2 with an Intel Core2 E6550 (2.33 GHz) CPU, 2 GB of memory, and a GeForce 8600 GT graphics card. The client program on the mobile phone was implemented in C#, and the mobile phone was an HTC T7373 running Windows Mobile 6.5 with a Qualcomm7200A, 528 MHz CPU, 288 MB of memory, and a 800×480 display resolution. The Digital Earth service was based on the ViWo System developed by Peking University (Wang *et al.* 2009), which can manage massive volumes of geographic data at the TB level and can provide different types of virtual reality effects and spatial analysis. MPEG-4 was chosen as the stream-media encoding protocol.

5. Prototype evaluation

5.1. MDE features

Using the Parasitic Model, all of the Digital Earth functions on the host computer were directly transplanted onto a mobile phone. Snapshots of the prototype are shown in Figure 5. Figure 5a shows the initial interface of MDE. The user can manipulate MDE with the keyboard and stylus to operate the virtual scene (see

Figure 5. Snapshots of MDE functions: (a) Interface (global view); (b) regional terrain; (c) visualization of a tornado; (d) virtual reality of the sea; (e) underwater simulations and (f) simulation of fire.

Figure 5b–f). Among these images, Figure 5b shows regional but detailed terrain on which 10,000 3D building models were placed. The total tri-patch count is over 50,000, which is extremely difficult for a mobile phone to manage using the traditional approach. Figure 5c shows the real-time visualization of a tornado based on measured data totaling more than 500 MB. Figures 5d–f show some virtual reality effects produced by a GPU still not available on mobile phones. Figure 5d shows sea surface simulations with light reflection and fluctuations rendered with a GPU cluster. Figure 5e shows an underwater simulation, including light beams, swimming fish, and seabed topography; and Figure 5f shows fire dispersion simulations on a cloudy day. In the above virtual scenes, the amount of original geographic data, the amount of computations, or both are far beyond the mobile phone's capabilities. However, the operations have still been accomplished smoothly using the Parasitic Model and the strategies proposed in this paper.

5.2. *Influences of the original scene dimension on the resulting amount of data*

The high cost of mobile communications requires MDE to reduce mobile network traffic as much as possible. Streaming compressed, time-series image data mentioned in Section 3.2 is one method to achieve this reduction, and the amount of output data could also be influenced by other factors, including the dimension of the source virtual scene, the target streaming dimension, the color bits, and the streaming bit rate. For successive experimentation with these factors, the target streaming dimension was set to 256×192 so that a series of integer scale factors could be achieved. All of the source virtual scenes of different dimensions were then scaled to 256×192, and the average output data were randomly selected out of 1000 frames. The statistics of the results are shown in Tables 1 and 2 and graphed as Figure 6.

Tables 1 and 2 and Figure 6 reveal that the output data without dimension scaling are greater than the outputs with dimension scaling. This rule is a valuable result for an MDE; if the target result dimension has been determined, then the source virtual

Table 1. Amount of output data for different source dimensions (ColorBit = 3).

Source render region	Destination media region	Bitrate			
		400,000	800,000	1,150,000	1,500,000
128×96	256×192	1578	1312	1578	1578
256×192	256×192	3274	3286	3281	3292
512×384	256×192	2622	2470	2691	2570
1024×768	256×192	1968	1838	1804	1858

Table 2. Amount of output data for different source dimensions (ColorBit = 4).

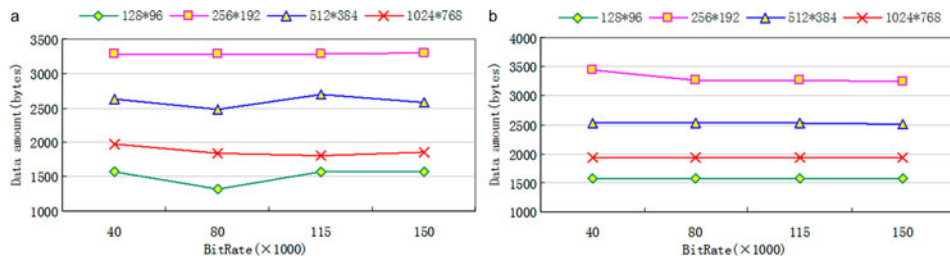| Source render region	Destination media region	Bitrate			
		400,000	800,000	1,150,000	1,500,000
128×96	256×192	1578	1581	1581	1578
256×192	256×192	3447	3261	3261	3251
512×384	256×192	2526	2524	2521	2511
1024×768	256×192	1934	1940	1942	1926

Figure 6. Data output as a function of the original dimension: (a) ColorBit = 3; (b) ColorBit = 4

scene dimension could be increased or decreased to achieve lower network traffic. In addition, we also found that when the source dimension is more than twice the target dimension, for example four times larger, the details, especially text, will be blurred, which restricts user-friendly manipulations of MDE. Thus, the optimal dimensional scale range should be (1, 2].

5.3. Analysis of time expended on network transfer and mobile phone display

Because the time spent on computing and rendering on the host computer can be reduced by enhancing the hardware performance, the response of MDE to manipulation is mainly associated with the time spent on transferring data through the network and displaying scenes on the mobile phone. During the experiment, the screen resolution of the mobile phone was 800×480, yielding an 800×378 viewable area after accounting for the title bar and task bar.

Based on the results of Section 5.2, two alternative approaches were employed and contrasted for real-time evaluation of MDE. Because the real dimension of the mobile phone was 800×378, the first approach, *Approach A*, was to render the virtual scene with the dimension of 800×378, which was encoded to 400×189 in the data stream to transfer through the network and then recovered to 800×378 by scaling on the mobile phone. The second approach, *Approach B*, was to render the virtual scene with the dimension of 800×378, which was encoded to streaming data directly without dimension scaling and decoded for display on the mobile phone. The time expenses of the two alternative approaches were determined and are shown in Figure 7.

Figure 7 shows that different approaches will result in different compositions of each of the two measures of time. Time spent on the display on the mobile phone of *Approach A* was longer than that of *Approach B*. This occurred because the scaling of the buffered frames was from 400×189 to 800×378, and displaying them cost more time than displaying those frames directly. Time spent on scaling is closely related to the computing performance of the mobile phone. For this factor, *Approach B* is superior to *Approach A*.

With respect to the time spent on the network, because the data were compressed by scaling down the frame dimension, the amount of data transferred using *Approach A* was less than *Approach B*, which resulted in less time and expense spent
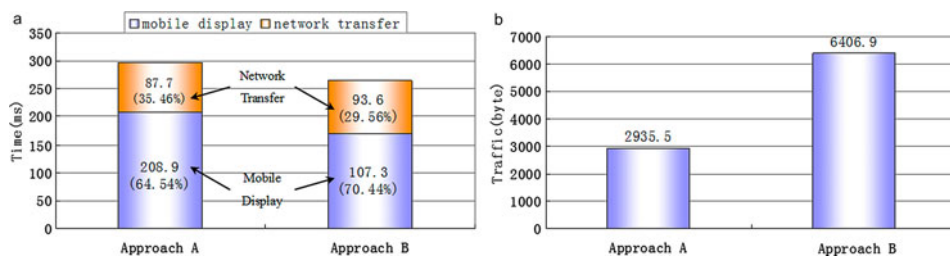

Figure 7. Time costs of the two alternative approaches: (a) time expended composite between the two alternative approaches and (b) Network traffic between the two alternative approaches

on the network than in *Approach B*. With respect to this factor, *Approach A* is superior to *Approach B*.

Because the total time is approximately between *Approach A* and *Approach B*, the user's needs should determine which approach to adopt. When the charge of network data communication is the main consideration, *Approach A* is preferred; when the virtual scene quality is the main consideration, *Approach B* is preferred.

5.4. Evaluation of data traffic reduction in the Parasitic Model

The data transferred through the network to build Digital Earth on a mobile phone based on the Parasitic Model are not the geographic source data but the encoded streaming data. One of the main strategies of the Parasitic Model is to overcome the barrier of the voluminous geographic data to be transferred through the low-bandwidth mobile network. The experiment evaluated the effect of the mechanism using *Approach A*, described in Section 5.3. Per the Parasitic Model, the host computer retrieved geographic source data including DEM, remote-sensing images, and other digital models through the Internet to construct a virtual scene. The streaming data were then encoded for the mobile phone to display. The amount of geographic source data retrieved by the host computer and the amount of streaming data retrieved by the mobile phone were determined, as shown in Table 3.

To make the result more objective, all of the virtual scenes on the host computer were random and fresh and had no duplicate content, maximizing the size of the data stream. Table 3 shows that the ratio of the output data stream to the original geographic data is nearly 1%. This result shows that the Parasitic Model is more effective than traditional models at transferring original data onto a mobile phone to construct an MDE. Because the geographic source data have been processed by the host computer, the result also implies that the Parasitic Model will save time spent on the network and reduce the computation pressure of processing these data on the mobile phone, especially for the current conditions of low-bandwidth mobile networks and low-performance mobile phones.

Table 3. Data traffic reduction achieved using the Parasitic Model.

Scene ID	Original geographic data (bytes)	Data transferred to mobile phone (bytes)	Reduction ratio (%)
1	518,910	2738	0.53
2	467,002	3770	0.81
3	251,401	4471	1.78
4	569,875	4777	0.84
5	382,806	2030	0.53
6	510,167	4195	0.82
7	477,360	4191	0.88
8	487,370	3951	0.81
9	456,573	3303	0.72

5.5. *The effects of network bandwidth on MDE performance*

The mobile network bandwidth will also influence the operation and experience of an MDE based on the Parasitic Model. During the experiment, different commercial mobile networks were employed to evaluate the influence of the mobile network's bandwidth on MDE, again using *Approach A*. The times spent on data transfer under WCDMA, GPRS, wireless LAN (Wi-Fi), and ActiveSync are shown in Figure 8. The network types in descending order of real-time performance are as follows: WCDMA ≈ ActiveSync > Wi-Fi > GPRS. Thus, using a wider-bandwidth network is another strategy to improve the real-time performance of an MDE based on the Parasitic Model.

Another interesting result shown in Figure 8 is that the performance of the *wireless* WCDMA is very close to that of the *wired* ActiveSync. The statistical differences between WCDMA and ActiveSync are shown in Figure 9. During the experiment, the MDE fluency was similar under both channels. Thus, it is reasonable to assume that much better performance will be achieved on the upcoming 4G mobile networks because 4G mobile networks have a wider bandwidth that is at least 50 times faster than 3G networks. When commercial 4G mobile networks are in operation, MDE based on the Parasitic Model will become more practical in terms of real-time responsiveness.
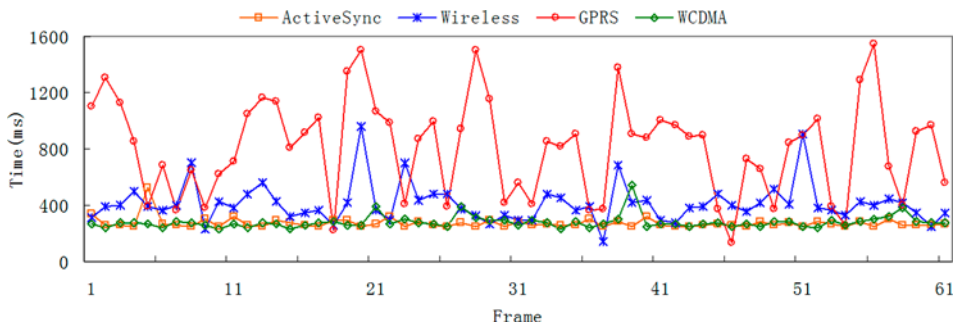

Figure 8. MDE performance using different networks.
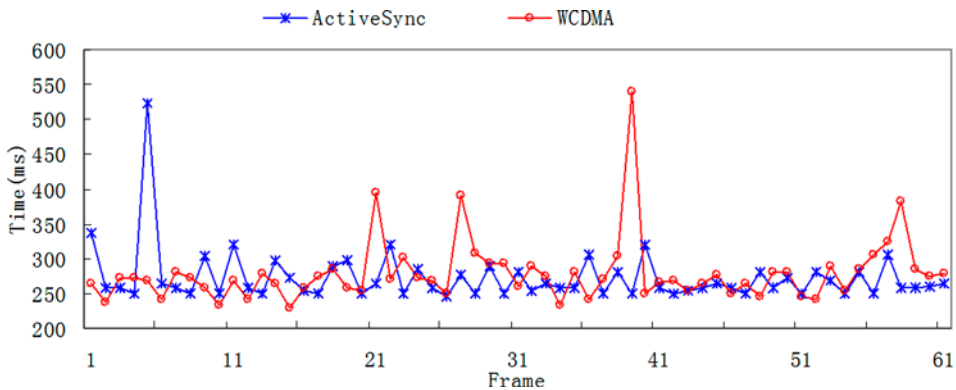

Figure 9. MDE performance under ActiveSync and WCDMA.

6. Discussion and conclusions

A stream-based framework, named the Parasitic Model, was proposed to run Digital Earth on a mobile phone through a mobile network. In this model, CRSN is accomplished by another device with superior performance instead of on the mobile phone. A streaming media method was employed to transfer the results because of its high compression ratio for time-series data, and an adaptive transfer strategy for the low-bandwidth mobile network was examined. A prototype was implemented and tested, and the results showed that MDE based on the Parasitic Model and key technologies can achieve quasi-real-time exploration.

The following topics can provide the basis for further discussion of this research.

6.1. On the pervasiveness of the Parasitic Model

As mentioned in Section 1, mobile operating systems vary, including iOS, Android, Symbian, Windows Mobile, and other systems, which makes it difficult to achieve a cross-platform MDE. However, based on the Parasitic Model that is proposed in this paper, the mobile phone need only handle simple, standard streaming data. The only difference between operating systems is different processes for encoding and decoding the streaming data, which is much easier than re-programming a Digital Earth application.

All of the features of Digital Earth achieved on the host computer can be transplanted directly onto the mobile phone without any modification. This scenario is especially convenient for upgrading Digital Earth functions. When functions are upgraded on the host computer, those functions will upgrade synchronously on all terminal devices. This mechanism does not require other versions of the Digital Earth system to be reconstructed and maintained, which means that MDE based on the Parasitic Model is pervasive on the software level.

In addition, with the host computer's help with CRSN, MDE based on the Parasitic Model can achieve superior functions beyond the target mobile phone's hardware configurations. In other words, functions and the function complexity of MDE are less constrained by the hardware than traditional models, which means that MDE based on the Parasitic Model is pervasive on the hardware level.

6.2. On the practicality of the Parasitic Model

Although most of the computation needs of CRSN are achieved on the host computer instead of on the mobile phone, the results of the rendered virtual scenes must still be sent to the mobile phone through the mobile network. Because the bandwidth of the current commercial mobile networks is still fairly low, this factor is key for a smooth MDE experience based on the Parasitic Model. Even so, the bandwidth usage is much lower than traditional approaches, which must retrieve a massive volume of geographic source data. The Parasitic Model ensures quasi-real-time performance when accessing Digital Earth on mobile phones, especially for the present case of low-bandwidth mobile networks. Of course, with the development and commercial applications of a higher-generation mobile network with wider bandwidth, such as 4G and 5G, the experiences will become much more user-friendly, as the experiment has proven.

6.3. On MDE based on the Parasitic Model and cloud computing

Although the Parasitic Model reduces computation demands on mobile phones, the host computers must address these demands, which means that high-performance host computers are necessary for high-quality services, especially when many mobile phone clients access the service synchronously. Fortunately, this problem can be overcome with the application of cloud computing, which is a promising research field in computing and storage (Yang *et al.* 2011). In fact, a commercial service for massive 3D model rendering based on cloud computing has been provided, for example, by the NVIDIA RealityServer.

Moreover, the idea of the Parasitic Model is somewhat similar to cloud computing. Cloud computing aims to accomplish centralized, high-capacity processing and storage, providing services for terminals with relatively poor computing or storage capability. In the future, the cloud computing center can act as the host of MDE based on the Parasitic Model, and with the help of the superior capabilities of cloud computing, better services can be promoted for faster and more complex scene rendering, more massive data processing, and higher concurrent access supporting numerous mobile terminals. Moreover, because cloud computing is business oriented and mobile phones have become 'integrant' equipment for people, MDE would extend more daily applications such as online, 3D map rendering for location-based services.

6.4. On the relationship between the Parasitic Model and the traditional strategy

MDE relying entirely on the ability of mobile phones will certainly be feasible with upgraded mobile technology, an increase in mobile network bandwidth, improvement of mobile phone hardware configurations, and a price decline for communications through mobile networks. However, as long as there are performance gaps between mobile phones and computers and between the Internet and mobile networks, the Parasitic Model will be an alternative approach for an MDE.

Notes

1. 2.08 Billion Now Use Internet; 5.28 Billion Use Cell Phones! Available from: http://nhne-pulse.org/2-08-billion-now-use-internet-5-28-billion-use-cell-phones [Accessed 9 November 2011].
2. Chinese mobile phone users reached 303 million last year. Available from: http://company.cnstock.com/industry/top/201105/1292357.htm [Accessed 9 November 2011].
3. Google Earth Help. Available from: http://earth.google.com/support/bin/answer.py?hl=en&answer=174898 [Accessed 9 November 2011].
4. Google Earth for Android User Guide. Available from: http://earth.google.com/support/bin/answer.py?hl=en&answer=174898 [Accessed 9 November 2011].

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