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Ling-Jyh Chen, *Member, IEEE,* and Ting-Kai Huang

Abstract—With wireless technologies extending to every part of our daily lives, mobile networking applications are becoming increasingly popular for accessing the Internet. Among them, web surfing is one of the most important applications because the World Wide Web, unencumbered by geographic boundaries, has accelerated the dissemination of information and knowledge via the Internet. In this paper, we propose a peer-to-peer mobile web surfing scheme called Collaborative Internet Access (CIA). Unlike traditional approaches, the proposed scheme implements a *Collaborative Forwarding* algorithm that takes advantage of opportunistic wireless connections to improve network capacity by exploiting the diversity of network mobility. Moreover, we propose a Scalable CIA scheme, called SCIA, which integrates the Layered Multiple Description Coding (LMDC) algorithm with the CIA scheme. SCIA allows the end user to preview the web content, even before the data has been completely transferred. Using simulations as well as real-world network scenarios, we demonstrate that the proposed scheme provides a better web surfing service than traditional schemes, and thus facilitates more effective web surfing on the go.

Index Terms—Internet Access, Peer-to-peer Networks, Opportunistic Networks, Scalable Coding.

1 Introduction

The last few years have seen an impressive growth in the number and variety of Internet applications. One striking success in this area has been the World Wide Web (WWW), which has accelerated the dissemination of information and knowledge by overcoming geographic boundaries. Wireless technologies represent another orthogonal area of growth in both wide area applications like 2.5G/3G and local area applications like 802.11b/g and Bluetooth. As wireless technologies continue to extend into every part of our working and living environments, a solution that can provide web surfing on the go is becoming increasingly desirable.

Proper handling of mobility is the key to the success of mobile networking applications, as complete coverage by wireless broadband (e.g., 2.5G/3G) is impossible [6]. In fact, recent studies have reported that intermittent network connections are inevitable for WLAN-based mobile users on a daily basis [15], [17]. Even so, Grossglauser et al. [28] showed that network capacity can be increased dramatically by exploiting node mobility as a type of multi-user diversity, and it is now widely accepted that opportunistic ad hoc connections can be useful for extending the coverage of wireless communications.

Several approaches have been proposed to allow mobile users to surf the web on the go [5], [8], [9], [10], [23], [29], [31], [32], [40], [41], [46]. The approaches can be categorized into three types: offline-based, cache-based, and Infostation-based. Offline-based and cache-based approaches facilitate mobile web surfing by prefetching web content to a local storage. Infostation-based approaches, on the other hand, support on-demand HTTP requests by deploying dedicated servers as bridges between the Internet and mobile networks. However, the capability of these approaches for mobile web surfing is limited because they are basically centralized and fail to exploit the diversity of network mobility.

To resolve this problem, we propose a peer-to-peer approach, called CIA, for mobile web surfing applications. In addition to combining the strengths of cache-based approaches (i.e., prefetching the most likely requested web pages to a local storage) and Infostation-based approaches (i.e., allowing on-demand HTTP requests), the CIA scheme implements a *Collaborative Forwarding* algorithm to further utilize opportunistic ad hoc connections and spare storage in the network. Moreover, we extend the CIA scheme by incorporating a scalable coding algorithm, called *Layered Multiple Description Coding (LMDC)*. The extended scheme, which we call SCIA, allows the end user to preview the desired web content, even before the data has been completely transferred. Using simulations as well as real-world mobility traces, we evaluate the proposed scheme in terms of service ratio and traffic consumption. The results show that the scheme significantly outperforms previous approaches in all test cases, while its traffic consumption remains moderate.

The remainder of this paper is organized as follows. In Section 2, we review related works on web surfing in mobile networks. In Section 3, we describe the CIA scheme and the *Collaborative Forwarding* feature used to disseminate web content in mobile networks. In Section 4, we present the SCIA scheme, which implements the Layered Multiple Description Coding algorithm to extend the CIA scheme with the capability of scalable

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data transmission. Section 5 presents a comprehensive set of simulation results, which we analyze and explain in detail. We then summarize our conclusions in Section 6.

2 Related Work

Mobile HTTP-based web access has been researched for a number of years, and several approaches have been proposed to enable web surfing on the go [5], [8], [9], [10], [23], [29], [31], [32], [40], [41], [46]. As mentioned earlier, the approaches can be classified into three types: offline-based, cache-based, and Infostation-based approaches.

Basically, offline-based approaches download web pages to a local storage in advance and allow users to access the documents, even when they are mobile or disconnected. Many widely used tools, such as `wget` [5] and `wwwoffle` [8], fall into this category, and most well known web browsers have built in functionalities to support offline mode operations. However, the main drawback of these approaches is that mobile users must download web documents manually, and they can only access a limited number of web pages that have been pre-fetched to a local storage.

Unlike offline-based approaches, cache-based approaches automatically download web pages that are considered likely to be requested in the near future. This is done in either a *push*-based [9], [23], [46] or a *pull*-based [31], [32], [41] fashion. More precisely, when *push*-based approaches are used, the content provider automatically supplies a mobile user with popularly requested web content as long as he/she is connected to the Internet and has free storage space. In contrast, under *pull*-based approaches, the mobile device automatically pulls (pre-fetches) web content (using its own content selection algorithm) without the HTTP requests issued manually by mobile users. Since cache-based approaches prepare web contents before they are actually requested, they generally perform more efficiently (in terms of service time) than offline-based approaches. The trade-off is that they incur a tremendous storage overhead in return for the performance gain (i.e., the more web pages they cache in the local storage, the greater the likelihood that they will be able to serve the next HTTP request without consuming extra Internet bandwidth). However, this is considered infeasible for emerging power/storage-constrained handheld devices. In addition, offline-based and cache-based approaches only allow Internet-capable users to download web pages; they do not provide a way for Internet-incapable users to access web content.

Infostation-based approaches provide web access for mobile users by installing Infostations that act as bridges between the Internet and mobile networks [26], such as Mobile Ad hoc NETworks (MANET) or Delay/Disruption-Tolerant Networks (DTN) [4]. The advantage of such approaches is that they allow mobile users to obtain web content from Infostations by using local wireless connections (e.g., WiFi and Bluetooth). Hence, mobile web surfing is possible, even when mobile users are not directly connected to the Internet. For example, [29] proposes a solution called *Mobile Hotspots*, which provides mobile Internet access in railway systems. Another approach called *Thedu* [10] uses Internet proxies to collect and pre-fetch web search results from pre-defined search engines; then, mobile users can search the results on the local storage of the nearest Infostations. Additionally, in [40], Ott et al. propose deploying Bundle Routers (BR) as Infostations to separate the Internet and DTNs. BRs are responsible for fetching web content from the Internet and forwarding the data to challenged mobile networks (i.e., where communication opportunities are intermittent and the network is frequently partitioned). Unlike previous schemes, the BR-based scheme requires mobile users' collaboration to forward data in a multihop and *store-carry-and-forward* fashion. It also allows users to access web content, even if they cannot locate an Infostation. However, the major shortcoming of the above approaches is that they require dedicated Infostations, which act as gateways to the Internet; thus, they suffer from scalability and single-point-of-failure problems.

3 Collaborative Internet Access (CIA)

In this section, we present our collaborative Internet access solution, called CIA, for mobile Internet download applications. The approach combines the strengths of offline-based, cache-based, and Infostation-based approaches with peer-to-peer networking concepts. As a result, it is better able to cope with the intermittent network connectivity caused by mobility, and can therefore provide better mobile Internet services. We describe CIA in detail in the following sub-sections.

3.1 CIA Architecture

There are two types of participating peers in the CIA system: *Gateway Peers* (GP) and *Vanilla Peers* (VP). GPs can connect to the Internet directly (by using, for example, GPRS, UMTS, WiMAX, or WiFi/Bluetooth via Internet Access Points). VPs do not have Internet access, but they have local wireless connection capabilities (by using, for example, WiFi, Bluetooth, or infrared via the ad hoc connection mode). Note that a mobile peer may switch from the GP mode to the VP mode (and vice versa) if it temporarily loses (or recovers) its Internet connection (e.g., when entering/leaving an elevator or a tunnel).

In the CIA system, there are two scenarios where a peer, A, can issue an Internet download request: if A is a GP, he can download the content himself immediately; otherwise, if A is a VP, he forwards his request, with a replication factor f (i.e., f copies of the request are input to the network), to the first f peers he meets in the network. Of course, the larger the value of f, the higher the number of participating peers that will be aware of

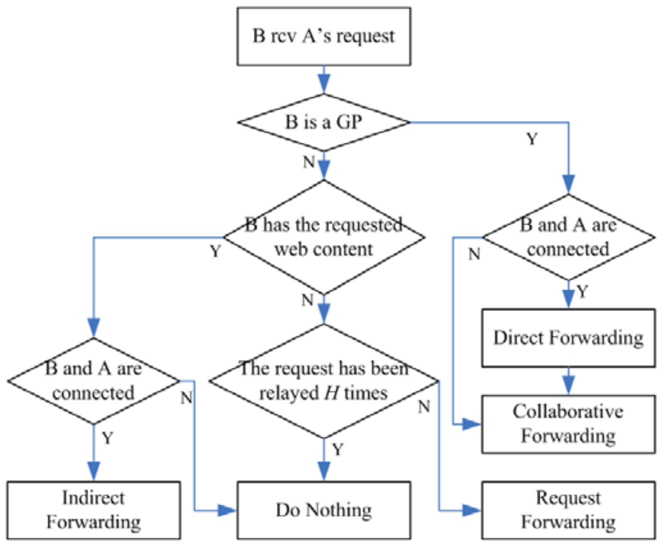


Fig. 1. Illustration of the CIA scheme's request process algorithm

A's request; however, the traffic and storage overhead also increase linearly as k increases.

The proposed CIA system is then applied as follows (see Fig. 1). Suppose B is another mobile peer that receives A's request. There are two cases:

1) *If B is a GP*, he immediately downloads the requested content from the Internet, and forwards it to A if they are connected directly (i.e., by the *Direct Forwarding* algorithm). Next, B disseminates the content to the mobile network using the *Collaborative Forwarding* algorithm, which we discuss in the next subsection. Note that the objective of the *Collaborative Forwarding* algorithm is to cache Internet content previously requested by peers in the network. This allows the CIA system to reduce redundant downloading when multiple peers request the same content. Of course, proper buffer management is required to further improve the performance of the CIA system. We defer a detailed discussion and evaluation of this issue to a future work.
2) *If B is a VP*, he first checks his local storage to determine whether the requested content has been cached, and then implements one of the following two options:
   a) *If B has the content requested by A*, he forwards it to A if they are connected directly (i.e., by the *Indirect Forwarding* algorithm); otherwise, he does nothing[1]. Note that the *Indirect Forwarding* phase is slightly different to the *Direct Forwarding* phase, since B may only have a portion of the requested content (which depends on the underlying *Collaborative Forwarding* algorithm); whereas all the content is forwarded in the *Direct Forwarding* phase.
   b) *If B does not have the content requested by A*, he forwards A's request to his next encountered peer, so long as the request has not been sent (from A to B) more than H times (i.e., by the *Request Forwarding* algorithm); otherwise, B does nothing.

In addition, the CIA system prioritizes the data transmissions such that *Direct Forwarding* has the highest priority, followed by *Request Forwarding*. Then, the other types of transmissions are processed on a first-come, first-served basis. The reason is that *Direct Forwarding* can complete a request-reply session of Internet downloading, and thus reduce the service time required of the transmitted content. Similarly, *Request Forwarding* propagates Internet download requests to the network, which increases the probability that the requests will reach GPs and thus be cached in the network.

3.2 Collaborative Forwarding

In this study, we incorporate the newly proposed HEC-PF algorithm [18] to provide collaborative forwarding for the CIA scheme[2]. The HEC-PF scheme is based on the H-EC scheme [19], which tries to forward the second copy of erasure coded blocks in sequence in H-EC's *Aggressive Forwarding* phase until the end of the network contact period. In contrast, the HEC-PF scheme implements the *Probabilistic Forwarding* algorithm and only enters the *Aggressive Forwarding* phase if a newly encountered node has a higher likelihood of successfully forwarding the message (called the *delivery probability*) to the destination peer than the current peer.

More specifically, if there are K nodes in the network, we denote the i-th node as X_i, the j-th node as X_j, the accumulated contact volume between the node pair X_i and X_j in the last T time unit as t_{X_i,X_j}, and the *delivery probability* for the node pair X_i and X_j with a distance of at most k-hops as $P^k_{X_i,X_j}$. The one-hop delivery probability from the source node (X_S) to the destination node (X_D) is given by the ratio of the accumulated contact volume over the overall contact volume[3], as shown in Eq. 1.

$$P^1_{X_S,X_D} = \frac{t_{X_S,X_D}}{\sum_{i=1}^{K} t_{X_S,X_i}} \quad (1)$$

The two-hop delivery probability, $P^2_{X_S,X_D}$, can be derived by Eq. 2. The equation is comprised of three components: the scaling constant, $\omega_2 \in [0...1]$, which decides the impact of two-hop message transfer on the overall delivery probability; the likelihood value, $1 - P^1_{X_S,X_D}$, which is the probability that a message can *not* be transmitted directly from node X_S to node X_D (i.e., it is impossible to complete the message delivery

1. This is the well-known "two-hop" scenario as used in [16], [28], [47].

2. Note that the collaborative forwarding algorithm can be replaced with other effective data dissemination schemes of opportunistic networks, such as MaxProp [14], MEED [33], and PRoPHET [37].

3. If $i == j$, $t_{X_i,X_j} = 0$.

in one hop); and the sum of the two-hop *transitive* delivery probability based on the *transitive* property, i.e., if node X_S frequently encounters node X_i, and node X_i frequently encounters node X_D, then X_i is a good candidate relay node for forwarding messages from X_S to X_D. Finally, the delivery probability of transferring a message from node X_S to node X_D is given by summing the two delivery probabilities, as shown by Eq. 3

$$P^2_{X_S,X_D} = \omega_2(1 - P^1_{X_S,X_D}) \sum_{\substack{1\le i\le K \\ i\ne S, i\ne D}} (P^1_{X_S,X_i} P^1_{X_i,X_D}) \quad (2)$$

$$P_{X_S,X_D} = P^1_{X_S,X_D} + P^2_{X_S,X_D} \quad (3)$$

Note that the decision about the *delivery probability* considers the *contact frequency* in the history and the *contact volume*, which represents the proportion of time that the two nodes were in contact in the previous time window. Consequently, the HEC-PF scheme is better able to achieve effective data forwarding in challenged networks.

4 Scalable Collaborative Internet Access (SCIA)

So far, we have discussed the CIA scheme that facilitates web surfing on the move by taking advantage of opportunistic connectivity (i.e., by using *Collaborative Forwarding*). However, because transferring complete web documents in an opportunistic network is quite difficult (i.e., it requires a much longer transfer time), the CIA scheme may not be really feasible, unless the receiver can read partial information from an incomplete web document. To address this issue, we propose integrating the CIA scheme with a scalable coding technique, called Layered Multiple Description Coding (LMDC) with unequal erasure protection, for mobile web surfing applications in opportunistic people networks. We call the resulting scheme *Scalable Collaborative Internet Access* (SCIA).

Layered MDC has been proposed as a means of combining Multiple Description Coding (MDC) [27] and Layered Coding [39] for emerging multicast and peer-to-peer audio/video streaming applications. More specifically, multiple descriptions are spread across multiple packets (or paths) via MDC, and transmitted to a collection of clients, thereby reducing packet loss due to network congestion or the failure of unreliable hosts. Applications of MDC include IP-level multicast [20] and application-level multicast [42], [43]. Moreover, by using Layered Coding, multimedia data can be encoded into different quality levels, so that clients can play the best possible video/audio quality level according to their capabilities, such as screen resolution and link bandwidth.

By combining MDC and Layered Coding, the Layered MDC scheme spreads the layered data across multiple packets with multiple descriptions. Then, clients can play the layered data as long as the required number of descriptions are received successfully. Of course, the more descriptions a client receives, the better the reconstructed data quality will be. In practice, the Layered MDC scheme is usually implemented in conjunction with Unequal Erasure Protection (UEP) [21]. The latter provides different levels of erasure protection to the Layered MDC blocks by adding different amounts of redundancy (i.e., the more essential the code blocks are, the more protection/redundancy UEP adds).

TABLE 1
Layered coding for web objects

Layers	MIME types
1	text/{html,css,plain,javascript,xml}; application/javascript
2	Layer 1 + image/{gif,jpeg,png,bmp,x-icon}
3	Layer 2 + application/{pdf,octet-stream,x-shockwave-flash}
4	Layer 3 + video
5	Layer 4 + others

More specifically, the LMDC scheme is applied to each MHTML document [44], which is a MIME (Multipurpose Internet Mail Extensions [12]) HTML document enclosing one or more objects, such as text, images, and videos. Unlike video transfer applications, the layered coding scheme encodes MHTML documents by looking up a pre-determined *codebook*, rather than splitting messages into equal-sized pieces. For instance, in Table 1, we present a codebook that is based on the MIME type of each web object.

In the codebook, Layer 1 web objects can be HTML documents (source codes only), cascading style sheets (CSS), java script, or plain text. Layer 2 contains images files in addition to Layer 1 objects. Layer 3 contains additional application objects (such as PDF files and flash video/games). Layer 4 contains additional video objects. Layer 5 contains other objects (e.g., audio and unknown objects). *Note that the design of the codebook can be customized and improved according to an object's size, semantics, importance, and other design choices.* The approach proposed in this paper is based on the generic LMDC concept.

As illustrated in Fig. 2, the LMDC scheme first encodes each MHTML document into k quality levels using layered coding. The layered document is then split among N packets ($N \ge k$) with unequal erasure protection on each layered piece. More precisely, the i-th layered piece contains the i-th layered document, excluding the $(i-1)$th layered piece. Unequal erasure protection is applied to each layered piece, such that the i-th piece is erasure coded with a replication factor r_i and split among N packets, i.e., *the i-th layered document can be successfully reconstructed from any N/r_i of the N packets* ($r_1 > r_2 > ... > r_{k-1} > r_k$ and $N \ge k$). The size of the i-th coded frame piece, b_i, can be obtained by Eq. 4, and the size of the resulting N packets, b_{packet}, can be obtained by Eq. 5. Note that, the i-th layered piece may be null if the original MHTML document does not have the corresponding types of objects specified in the

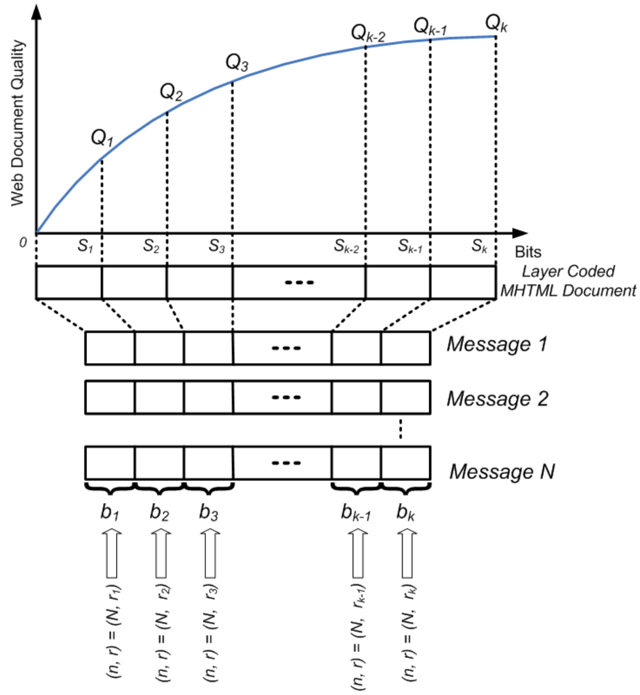


Fig. 2. Illustration of the Layered MDC scheme with unequal erasure protection. Each web document is encoded into k quality levels using layered coding. The i-th quality level content is erasure protected with replication factor r_i and split equally among N relays ($r_1 > r_2 > ... > r_{k-1} > r_k$ and $N \geq k$).

codebook.

$$b_i = \frac{(S_i - S_{i-1}) \times r_i}{N} = \frac{S_k r_i}{kN} \quad (4)$$

$$b_{packet} = \sum_{i=1}^{k} b_i = \frac{S_k}{kN} \sum_{i=1}^{k} r_i \quad (5)$$

For simplicity, in this study, we let $r_i = N/i$ and $N = k$. The values of b_i and b_{packet} can be obtained by Eq. 6 and 7 respectively; and the traffic consumption of the LMDC scheme, $b_{overhead}$, can be obtained by Eq. 8. Since k is a positive integer, one can conclude that (a) $b_{overhead} = 0$ when $N = k = 1$ (i.e., no LMDC); and (b) $b_{overhead} > 0$ otherwise.

$$b_i = \frac{S_k}{ik} \quad (6)$$

$$b_{packet} = \frac{S_k}{k} \sum_{i=1}^{k} \frac{1}{i} \quad (7)$$

$$b_{traffic} = N b_{packet} = S_k \sum_{i=1}^{k} \frac{1}{i} \quad (8)$$

For example, using the codebook shown in Table 1, each MHTML document is encoded into 5 layers using LMDC (i.e., $k = 5$). Fig. 3 shows the quality of sample web documents in Layers 1, 2, and 3. As shown in the figure, Layer 1 provides basic text-only descriptions at the lowest quality level, Layer 2 adds images of intermediate quality to the descriptions, and Layer 3 adds flash animations of the highest quality. The quality of the web document improves incrementally as the number of layers or the amount of received data increases.

TABLE 2
Object properties of the selected web documents

Object types	Request (%)	Avg. Size (bytes)
Layer 1	27.81	9,082
Layer 2 excluding Layer 1 objects	63.11	6,974
Layer 3 excluding Layer 2 objects	8.17	66,725
Layer 4 excluding Layer 3 objects	0.15	2,028,783
Layer 5 excluding Layer 4 objects	0.76	182,289

5 Evaluation

In this section, we evaluate the web surfing performance of the proposed schemes in opportunistic people networks. We implemented the CIA, SCIA, and Mobile Hotspots schemes and performed simulations in DTNSIM [3], a java based DTN simulator. As mentioned earlier, Mobile Hotspots is an Infostation-based approach with mobile Internet gateways, but without a collaborative forwarding feature (i.e., a mobile user can only download web pages if he encounters one of the gateways).

In each simulation run, we randomly select γ mobile peers as GPs (with unlimited Internet connection bandwidth) and 20% of the other peers (i.e., VPs) as web surfers. The GPs archive web documents and deliver them to the opportunistic network after LMDC coding. Each web document is converted into MHTML format [44], which is a MIME (Multipurpose Internet Mail Extensions [12]) HTML document containing one or more objects, such as text, images, or videos. To ensure that the simulation was realistic, we selected the top 500 requested web documents according to the hit-count statistics of our campus proxy server for the period Apr.'06 to Sept.'06, and applied LMDC to the selected documents in the simulation. Table 2 shows the embedded object properties of the selected web documents, and Table 3 shows the distribution of the selected documents that exhibited the best possible quality with limited layers (i.e., a web document may exhibit the best possible quality with fewer layers if it does not contain objects located in higher layers). The average number of layers required by the best possible quality documents in this study was 2.56.

For simplicity, we assume that web surfers only issue HTTP requests in the first 10% of the simulation time, with a Poisson rate of 1,800 seconds/request. We also assume that data transmission between mobile peers is using Bluetooth 2.0 EDR [1] with a fixed rate of 2Mbps, and that each HTTP request can be relayed at most 2-

(a) Layer 1 (b) Layer 2 (c) Layer 3

Fig. 3. Examples of the NBA.com web page after layered coding (Layer 1 only contains text; Layer 2 contains images in addition to Layer 1 objects; and Layer 3 contains flash animations in addition to Layer 2 objects).

TABLE 3
The distribution of the number of layers of the selected web documents required to yield a full quality document.

Layer #	Number of documents	% of documents
Layer 1	0	0%
Layer 2	240	48%
Layer 3	240	48%
Layer 4	15	3%
Layer 5	5	1%

TABLE 4
The properties of the three network scenarios

Trace Name	iMote	UCSD	IBM
Device	iMote	PDA	Laptop
Network Type	Bluetooth	WiFi	WiFi
Duration (days)	3	77	29
Devices participating	274	273	1,366
Number of contacts	28,217	195,364	1,176,264
Avg # Contacts / pair / day	0.25148	0.06834	0.04548

hops (i.e., H=2) with the replication factor f equal to 4 [4]. For the *Collaborative Forwarding* scheme, the replication factor of the erasure coding r is set to 2; each coded message is fragmented into 16 equal-sized blocks (i.e., N = 16); the sliding time window T (used to estimate the delivery probability) is set to 1,000 seconds; the scaling constant ω is set to 0.25; and the buffer size of each mobile peer is unlimited. All the simulation results presented in this section are based on the average performance of 200 simulation runs.

5.1 Evaluation Scenarios

We evaluate three network scenarios based on realistic wireless network traces, namely, the iMote [2], UCSD [7], and IBM [11] traces, which are publicly available for research purposes and correspond to the opportunistic people networks of conference, campus, and enterprise scenarios, respectively. Table 4 outlines the basic properties of the network scenarios.

The iMote trace is a human mobility trace collected at the 2005 IEEE Infocom conference. It was aggregated from 41 Bluetooth-based iMote devices distributed to the student attendees for the duration of the 3-day conference. Each iMote device was pre-configured to periodically broadcast query packets to find other Bluetooth devices within range, and record the devices that responded to the queries. In addition to the distributed iMote devices, another 233 devices were recorded in the trace. They may have been other Bluetooth-enabled devices (e.g., PDAs, cell phones, or headsets) used during the conference. For simplicity, we assume there is a network contact between two Bluetooth devices if there are query-and-response interactions between them.

The UCSD trace is client-based and records the availability of WiFi-based access points (APs) for each participating portable device (e.g., PDAs and laptops) on the UCSD campus. The network trace covers a two and half-month period, and there are 273 participating devices. Similar to [17], [19], [30], we assume that two participating devices in ad hoc mode encounter a communication opportunity (i.e., a network contact) if they are associated with the same AP at the same time.

The IBM trace is also a client-based based trace collected by 177 Wi-Fi access points located in three buildings of the IBM Watson Research Center. The trace is about 29 days long, and 1,366 unique MAC addresses are recorded in the trace. Similar to [11], we assume that each unique MAC address corresponds to a user, even though it is possible for a single user to have more than one MAC address or for users to trade cards with each other. Again, we assume that two users encounter a network contact if they are both associated with the

4. Generally, the larger values of H and f, the better delivery ratio performance can be achieved by collaborative forwarding. However, the traffic overhead will increase substantially with the values of H and f. In this study, we let $H = 2$ and $f = 4$ for simplicity, and a more comprehensive set of evaluation results w.r.t. various values of H and r can be found in [18].

same AP at the same time.

5.2 Evaluation I: Service and Response Time Performance

Here, we evaluate the performance of the SCIA, CIA, and Mobile Hotspots schemes, in terms of *service time* and *response time*. By service time, we mean the interval between the time a HTTP request is issued and the time the last byte of the requested web content is downloaded; and by response time, we mean the interval between the time a HTTP request is issued and the time the first 'playable' version of web content, i.e., the lowest quality level document, is downloaded. Note that the response time performance of the CIA and Mobile Hotspots schemes is equivalent to the service time performance, since they do not implement scalable coding (i.e., LMDC) within the data dissemination schemes. Figs. 4, 5, and 6 show the experiment results as Cumulative Distribution Function (CDF) curves for various numbers of GPs (i.e., $\gamma = 5\%, 10\%, 15\%$) in the iMote, UCSD, and IBM scenarios, respectively.

¿From Figures 4, 5, and 6, we observe that the service time performance of the SCIA scheme is about the same as that of the CIA scheme, and both outperform the Mobile Hotspots scheme in all test cases. This confirms our intuition that *collaborative forwarding* can utilize opportunistic connections, and thus better exploit the diversity of network mobility.

We also observe that, in all schemes, the service ratio improves as the value of γ increases. For instance, when γ increases from 5% to 15%, the service ratio of the SCIA scheme increases as follows: from 34% to 42% in the iMote scenario, from 88% to 93% in the UCSD scenario, and from 84% to 93% in the IBM scenario. The reason is that, as γ increases, the number of the GP nodes in the network also increases. As a result, it is more likely that VP nodes will be able to access the Internet directly (i.e., by using direct forwarding from GPs) or indirectly (i.e., via multihopping to GPs). Moreover, the results show that the response time performance of the SCIA scheme is superior to the service time performance of the SCIA and CIA schemes in all test cases.

5.3 Evaluation II: Perceived Web Surfing Quality

Next, we evaluate the performance of the SCIA, CIA, and Mobile Hotspots schemes in terms of the user-perceived web surfing quality (i.e., the largest layer number of a layered web document that can be reconstructed by the end user) in opportunistic people networks. Figures 7, 8, and 9 show the normalized average quality of web surfing (for 2.56, which is the average number of layers required for the best possible quality documents) in the iMote, USCD, and IBM scenarios respectively.

The results in Figures 7, 8, and 9 clearly show that, for all schemes, the average surfing quality improves over time and eventually converges after a certain period. The reason is very straightforward: a web surfer has more chances of making more contacts in the network as time goes by, and is thus more likely to obtain the requested web documents. Moreover, the results show that the SCIA and CIA schemes outperform the Mobile Hotspots scheme in all test cases, which again confirms that the Collaborative Forwarding algorithm can better exploit the network mobility to increase network capacity. Finally, the results show that the SCIA scheme outperforms the CIA scheme in all cases. This is because the LMDC mechanism spreads web documents more widely over the network, and allows the receiver to preview parts of a document, even before it has been transferred completely. In contrast, under CIA, the end user can not play a partially received web document.

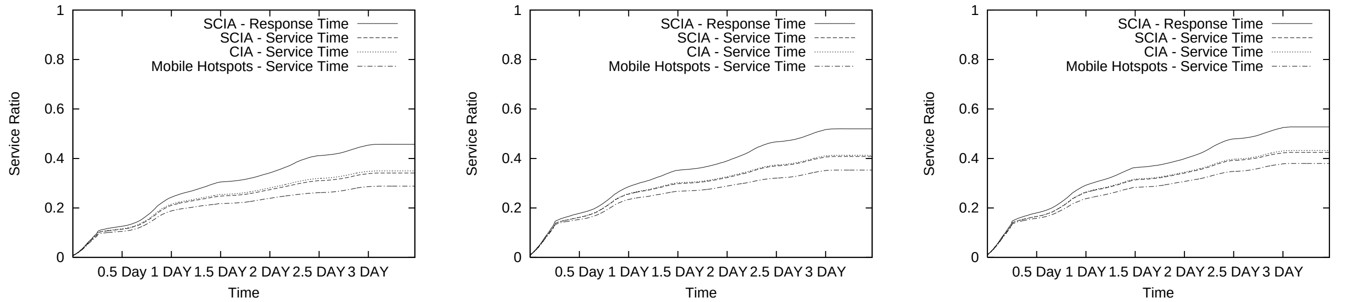
We also compare the average surfing quality of each received web document, which is more representative of the surfing experience of end users. Figures 10, 11, and 12 show the CDF distribution of the web document quality received by a surfer, with $\gamma = 15$ [5], at three time points (i.e., 10%, 20%, and 80% of the simulation time) in the iMote, UCSD, and IBM scenarios respectively.

In Figures 10, 11, and 12, it is apparent that, for all schemes, the CDF curves fall over time: the curve for 20% of the simulation time is lower than that for 10% of the simulation time, and the curve for 80% of the simulation time is lower than that for 20% of the simulation time. The results are consistent with our intuition that the quality of web document transfer should improve as the overall delivery latency increases. Moreover, the curves of the SCIA scheme are consistently lower than those of the CIA scheme, and the CIA scheme has lower curves than the Mobile Hotspots scheme.

The results also show that under the Mobile Hotspots scheme, about 62% of web documents are unobtainable (i.e., the quality level is equal to 0), even after 80% of the simulation time in the iMote scenario (11% and 17% of web documents are unobtainable in the UCSD and IBM scenarios respectively). In contrast, in the iMote scenario, only about 57% of documents are unobtainable at the same time point when the CIA scheme is used (3% and 4% documents are unobtainable in the UCSD and IBM scenarios respectively), and 51% of documents are unobtainable at the same time point when the CIA scheme is used (2% and 3% documents are unobtainable in the UCSD and IBM scenarios respectively). Moreover, since the CIA and Mobile Hotspots schemes only provide "one-or-zero" delivery of web documents, they do not allow scalable web surfing when only partial data is received; thus, there are no received Layer 1 quality web documents in the simulation (using the same set of 500 web documents shown in Table 3). However, the SCIA scheme allows web surfers to browse lower quality (Layer 1 quality) web documents before they have been transferred completely.

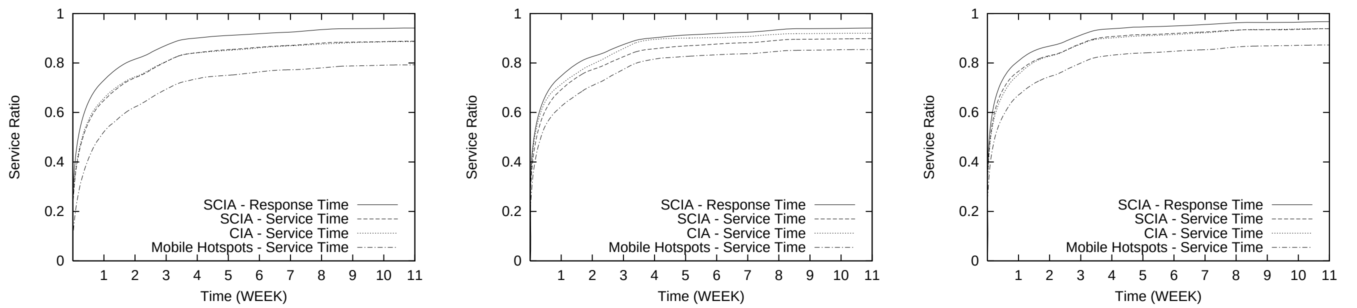
To sum up, the evaluation results demonstrate that

5. We decide to omit the results of $\gamma = 5$ and $\gamma = 10$ in this paper due to space limitations.



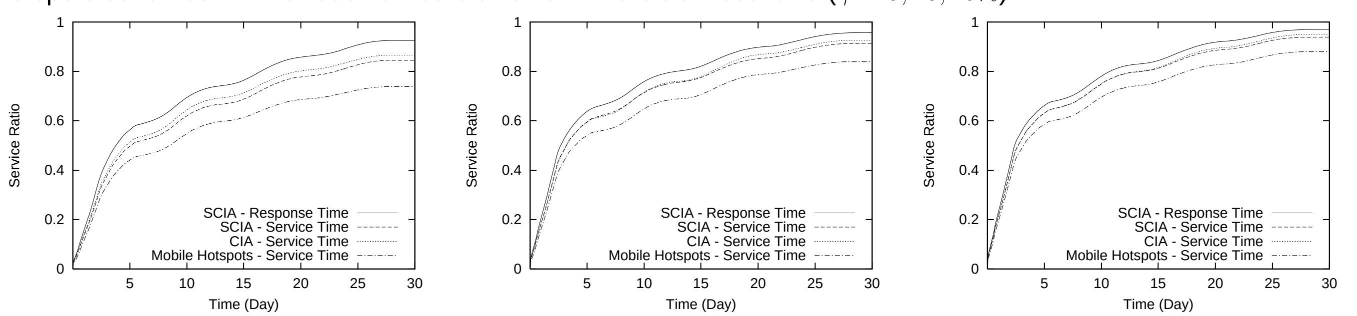
(a) $\gamma = 5\%$ (b) $\gamma = 10\%$ (c) $\gamma = 15\%$

Fig. 4. Comparison of the performance, in terms of service time and response time, of the SCIA, CIA, and Mobile Hotspots schemes with various numbers of GPs in the iMote scenario ($\gamma = 5, 10, 15\%$)



(a) $\gamma = 5\%$ (b) $\gamma = 10\%$ (c) $\gamma = 15\%$

Fig. 5. Comparison of the performance, in terms of service time and response time, of the SCIA, CIA, and Mobile Hotspots schemes with various numbers of GPs in the UCSD scenario ($\gamma = 5, 10, 15\%$)



(a) $\gamma = 5\%$ (b) $\gamma = 10\%$ (c) $\gamma = 15\%$

Fig. 6. Comparison of the performance, in terms of service time and response time, of the SCIA, CIA, and Mobile Hotspots schemes with various numbers of GPs in the IBM scenario ($\gamma = 5, 10, 15\%$)

the SCIA scheme enhances web document transfer in opportunistic people networks by allowing surfers to preview lower quality web documents. Thus, it can cope with link outages better than the other schemes, and provide scalable web surfing in challenging network environments.

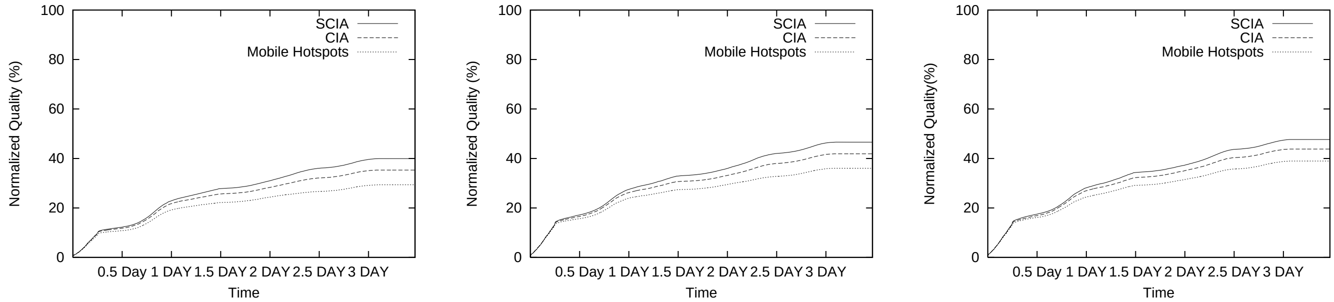
5.4 Evaluation III: Traffic Overhead

Next, we evaluate the traffic consumption of the SCIA, CIA, and Mobile Hotspots schemes. The simulation settings are the same as those in the previous subsection, and the results are based on the average traffic consumption of 200 simulations. Table 5 shows the results where the normalized overhead is derived by taking the ratio of the traffic consumption of the SCIA scheme over the CIA scheme, and the ratio of the traffic consumption of the CIA scheme over the Mobile Hotspots scheme.

The results show that the traffic overhead of the SCIA scheme is about 1.5 times more than that of the CIA scheme. This is because the SCIA scheme uses the LMDC algorithm. The traffic overhead can be controlled by the employed ri parameters, as defined in Eq. 8. For instance, using Eq. 8 and the distribution of the requested HTML documents shown in Table 3, the upper bound of the normalized traffic consumption (SCIA / CIA) can be obtained by

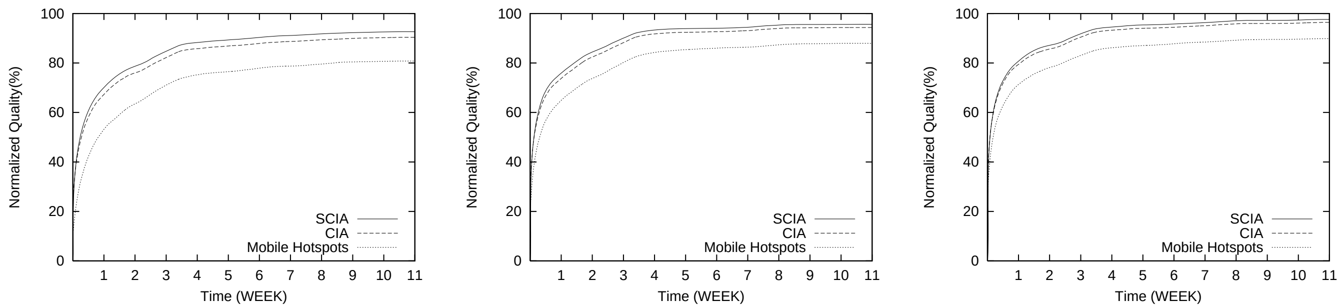
$$\begin{aligned} &0\% \times \textstyle\sum_{i=1}^{1} \frac{1}{i} + 48\% \times \sum_{i=1}^{2} \frac{1}{i} + 48\% \times \sum_{i=1}^{3} \frac{1}{i} \\ &+3\% \times \textstyle\sum_{i=1}^{4} \frac{1}{i} + 1\% \times \sum_{i=1}^{5} \frac{1}{i} \approx 1.69. \end{aligned} \tag{9}$$

Additionally, the results show that the traffic overhead of the CIA scheme is about three times more than that of the Mobile Hotspots scheme, and the normalized



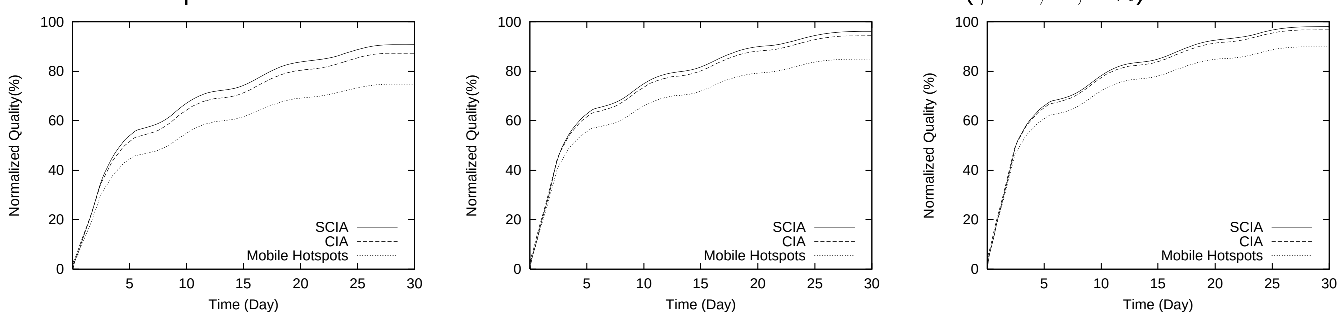
(a) $\gamma = 5\%$ (b) $\gamma = 10\%$ (c) $\gamma = 15\%$

Fig. 7. Comparison of the performance, in terms of the normalized average quality of web surfing, of the SCIA, CIA, and Mobile Hotspots schemes with various numbers of GPs in the iMote scenario ($\gamma = 5, 10, 15\%$)



(a) $\gamma = 5\%$ (b) $\gamma = 10\%$ (c) $\gamma = 15\%$

Fig. 8. Comparison of the performance, in terms of the normalized average quality of web surfing, of the SCIA, CIA, and Mobile Hotspots schemes with various numbers of GPs in the UCSD scenario ($\gamma = 5, 10, 15\%$)



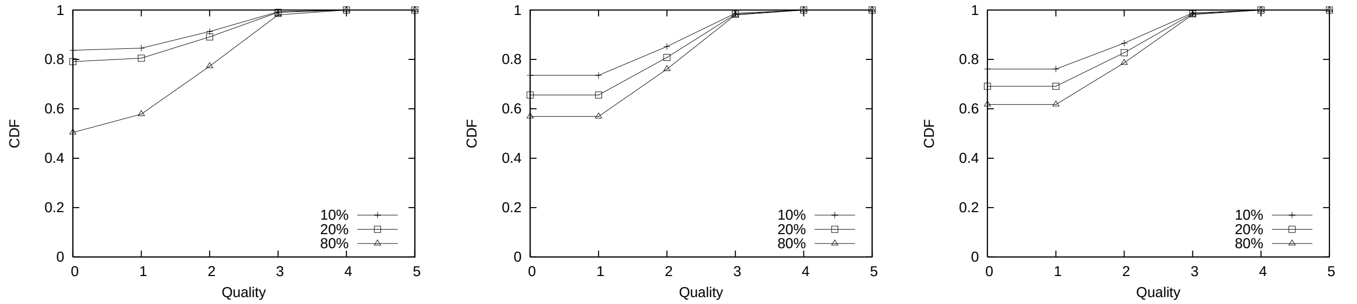
(a) $\gamma = 5\%$ (b) $\gamma = 10\%$ (c) $\gamma = 15\%$

Fig. 9. Comparison of the performance, in terms of the normalized average quality of web surfing, of the SCIA, CIA, and Mobile Hotspots schemes with various numbers of GPs in the IBM scenario ($\gamma = 5, 10, 15\%$)

TABLE 5
Comparison of the traffic consumption of the SCIA, CIA, and Mobile Hotspots schemes (Units: Mbytes)

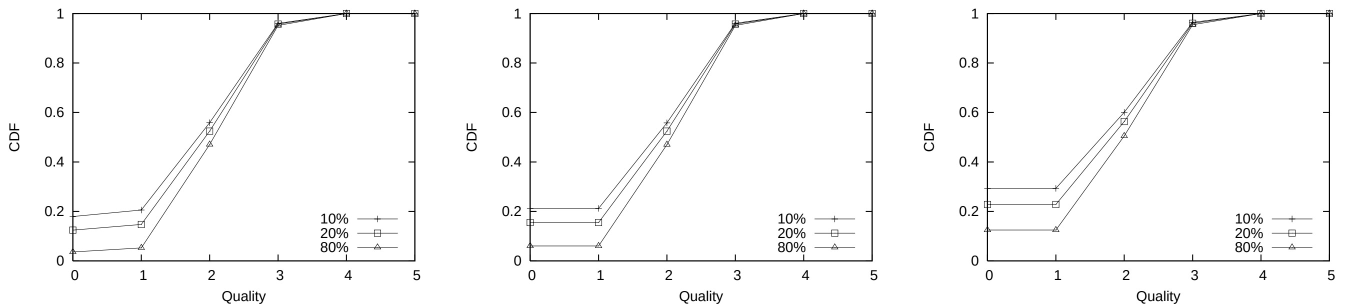
					Normalized Overhead	
Scenario	γ	SCIA	CIA	Mobile Hotspots	SCIA / CIA	CIA / Mobile Hostpots
iMote	5%	5,369	4,101	1,217	1.31	3.37
	10%	5,547	4,137	1,395	1.34	2.97
	15%	5,102	3,871	1,412	1.32	2.74
UCSD	5%	249,850	175,524	61,755	1.42	2.84
	10%	252,997	175,547	65,772	1.44	2.67
	15%	257,684	172,819	66,949	1.49	2.58
IBM	5%	441,976	326,927	111,052	1.35	2.94
	10%	477,387	340,430	123,837	1.40	2.75
	15%	483,433	333,696	127,963	1.45	2.61

overhead decreases as γ increases. Note that the traffic consumption is upper bound by the collaborative forwarding algorithm. For instance, in our simulation, the upper bound of the normalized overhead is 4 (i.e., 2 due to the replication factor of erasure coding, times 2 due to the collaboration forwarding scheme). Of course, the



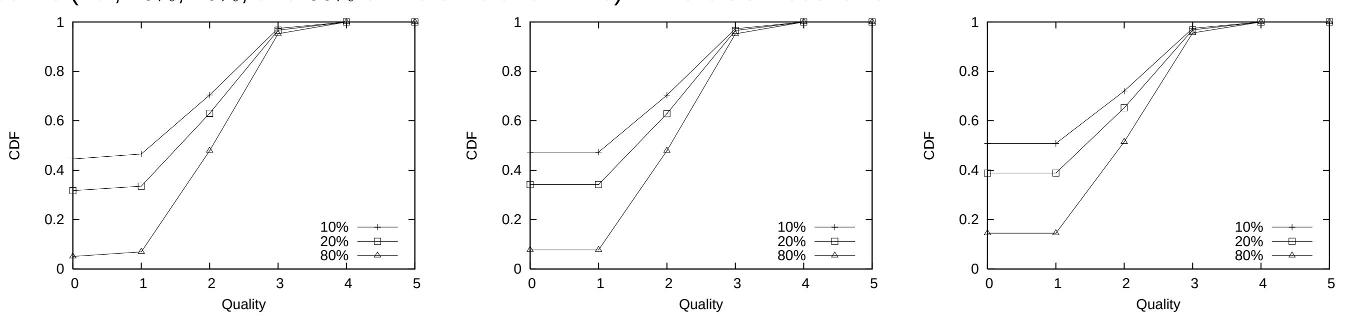
(a) SCIA (b) CIA (c) Mobile Hotspots

Fig. 10. The CDF distribution of the average web document quality received by a surfer, with $\gamma = 15$, at three time points (i.e., 10%, 20%, and 80% of the simulation time) in the iMote scenario.



(a) SCIA (b) CIA (c) Mobile Hotspots

Fig. 11. The CDF distribution of the average web document quality received by a surfer, with $\gamma = 15$, at three time points (i.e., 10%, 20%, and 80% of the simulation time) in the UCSD scenario.



(a) SCIA (b) CIA (c) Mobile Hotspots

Fig. 12. The CDF distribution of the average web document quality received by a surfer, with $\gamma = 15$, at three time points (i.e., 10%, 20%, and 80% of the simulation time) in the IBM scenario.

traffic consumption of the CIA scheme can be adjusted by tuning the replication factor of erasure coding or replacing the collaborative forwarding algorithm. Generally, the more replicated data stored in the network, the better will be the service ratio achieved by the CIA scheme.

5.5 Discussion

We have demonstrated that the proposed CIA/SCIA schemes have the potential to provide effective and efficient mobile web surfing services in opportunistic people networks. The success of the proposed approaches depends to a great extent on close collaboration among network participants; however, on the downside, the proposed approaches may become very vulnerable if there are uncooperative peers in the network. Here, we discuss the major challenges faced by the proposed CIA/SCIA schemes, and present potential solutions to these issues.

First, based on the different levels of malicious behavior, the proposed schemes may suffer four types of network attacks, namely *Dropping All Packets*, *Flooding*, *Routing Information Falsification*, and *Ack Counterfeiting* [13]. More precisely, while the *Dropping All Packets* attack intentionally drops all received packets without forwarding to other peers (a.k.a. black holes [25]), the *Flooding* attack continuously sends fake data from any node to any node, to drain available network resources (e.g., the energy and buffer of network peers). The *Routing Information Falsification* attack creates erroneous routing information that may cause the network to delay or lose messages altogether, and the *Ack Counterfeiting* attack propagates false acknowledgments of in-transit packets that can cut off possibly viable paths to the destination. A potential solution to the issues of uncooperative behavior is to incorporate an incentive-based mechanism (e.g., [24], [34]) into the proposed schemes. Such a mechanism should be able to encourage network peers to contribute their resources and discourage them from engaging in malicious behavior [35]. Consequently, the proposed CIA/SCIA schemes would benefit from the tight collaboration among network peers.

Second, since the proposed CIA/SCIA approaches operate on a store-carry-and-forward basis [45], they tend to buffer large amounts of data in the network. Moreover, the required network storage space increases dramatically as the number of web requests increases. Consequently, buffer overflow may occur frequently such that some in-transit packets have to be dropped, which may substantially degrade the performance of the proposed schemes in terms of the delivery ratio (especially when the number of remaining packets is less than the number of packets required to reconstruct the message). For simplicity, in this study, we assume that each peer has an infinite buffer size. However, ideally, the solution should consider the nature of the employed routing algorithm, and apply an appropriate queuing policy to manage the network storage space [22], [36], [38]. We defer a detailed evaluation of this issue to a future work.

Finally, for web pages that are updated frequently (e.g., news, blogs, albums, and wiki-based web pages), a requested web document is likely to have experienced several updates/revisions between the time a request for the document was initiated and the time the end user received it. As a result, the end user may receive multiple versions of the same web document and have difficulty reconstructing it. A practical solution to this issue is to timestamp each packet when a web document is input to the network by the GP node. Then, the end user is only allowed to reconstruct the document if he has collected a sufficient number of packets with the same timestamp.

6 Conclusion

We have proposed an approach called CIA to improve mobile web surfing applications via *Collaborative Forwarding*. In addition, we have proposed an enhanced scheme, called SCIA, which integrates the Layered Multiple Description Coding with the CIA scheme to provide scalable Internet access in opportunistic people networks. Unlike traditional approaches, the proposed schemes do not need dedicated servers to form bridges between the Internet and mobile networks. Moreover, both schemes implement a *Collaborative Forwarding* feature that makes better use of opportunistic connections among mobile peers, and thereby improves network capacity by exploiting the diversity of network mobility. Using simulations as well as real-world network scenarios, we evaluated the proposed schemes against a traditional approach called Mobile Hotspots. The results demonstrate that our scheme can achieve better service ratios with moderate traffic consumption in all test cases. Moreover, we have shown that the SCIA scheme enables the end user to "preview" lower quality web documents, even before the data has been completely transferred, which improves the overall viewing experience. The effectiveness of our proposed schemes makes them ideal solutions that can facilitate mobile web surfing in opportunistic people networks.

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