Interest-based Cloud-facilitated Opportunistic Networking

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ABSTRACT

Opportunistic networking requires timely discovery of locally available peers with an incentive to communicate, i.e., that share an *interest* in an application or content. To overcome the absence of mobile OS support for incorporation of interests in peer discovery, we propose ICON, an integrated mobile cloud solution that discovers mobile peers in communication range through a cloud service.

Peers manage and update their current location and interests at the cloud service using the device's 3G connection. Once a peer with matching interests is in range, the cloud service opportunistically triggers a local 802.11 network between the peers' devices. We show the feasibility, performance, and energy efficiency of ICON and highlight its real-world applicability. Through this mechanism, ICON allows the ready deployment of opportunistic applications without additional OS support, bringing opportunistic network services to unmodified consumer devices.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design—*Wireless communication, Network communications, Store and forward networks*

Keywords

Opportunistic Networking, Mobile Cloud Solution, Interest-based Networking

1. INTRODUCTION

Opportunistic networking builds on exploiting uncoordinated contacts between mobile wireless devices for communication and content exchange. The resulting network structure then enables diverse and novel applications [9, 10, 16, 18, 22] as well as offloading of cellular traffic to relieve the overloaded carrier infrastructure [8, 14, 17]. The ubiquitous proliferation of mobile wireless devices, most notably smartphones, thereby constitutes a readily available critical mass of target devices to establish the envisioned network.

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Still, realizing the basic assumption of opportunistic device-to-device connectivity remains an open problem. Next to establishing a common network between devices [11,23], we argue that this primarily entails determining who to communicate with, i.e., discovering devices with applications and content of matching *interest*. Device [3] and network discovery approaches, i.e., 802.11 scans, are unable to express the multitude and availability of content of interest at devices and in networks, respectively. Mobile devices and applications can thus not determine whether encountered devices can match their interests or content requests. Conversely, content discovery [19] requires a pre-existing, shared network. Similar, smartphone operating systems do not yet support the networking functionality required by approaches [4, 25] that bridge this gap between device, network, and content discovery by encoding semantics in the discovery process.

In this paper, we thus propose ICON (Interest-based Cloud-facilitated Opportunistic Networking), a readily deployable and smartphone-tailored interim solution to foster opportunistic networking in urban areas. Orthogonal to transferring protocol operation [26] or mobile-to-mobile communication [12] to the cloud, ICON leverages the rising worldwide proliferation of mobile data plans [5] to enable interest-based device discovery and dedicated *local* 802.11 networking. Specifically, ICON manages the location and digests of user interests, i.e., requested and provided content and applications, at a centralized service, e.g., in the cloud. Once users with matching interests are in transmission range, ICON triggers the purposeful tethering of WPA2-secure 802.11 networks to exchange the content of interest, improving on inaccurate device or network selection. We implemented ICON in an Android application, specifically tailored to smartphones to foster real-world adoption.

Higher-context services, such as micro payment schemes, content certification, and trust establishment, can further increase adoption by providing incentives and insurances against misuse. Leveraging the cloud service as a (trusted) proxy renders such services immediately deployable, mitigating the inherent difficulty of realizing and enforcing them in uncoordinated distributed settings.

In contrast to existing approaches (Section 2), ICON emphasizes location- and interest-based opportunistic networking without prior coordination of a shared or application-specific *local* network (Section 3). We evaluate our design in terms of feasibility, performance, and energy consumption (Section 4). Last, we discuss application and service integration, scalability, and deployment considerations of ICON (Section 5).

2. RELATED WORK

ICON relates to approaches that enable opportunistic networking, leverage user interests and locations, or build on mobile cloud solutions. By effect, it relates to data offloading in mobile networks.

Enabling opportunistic networking. WiFi-Opp [23] alternates mobile devices between sleep, tethered 802.11 AP, and client phases to support opportunistic establishment of shared networks and save energy. Complementarily, the authors of [11] analyze the feasibility of using existing APs for opportunistic communication. The authors further propose mechanisms for device and service discovery at APs.

While sharing the same motivation, ICON approaches opportunistic networking as a result of common interests between users, thereby preventing futile associations. Realizing the intuitive notion of communication between nearby users of common interests, we expect ICON to facilitate real-world adoption of diverse opportunistic applications.

Interest-based opportunistic networking. In [9], as part of the PodNet project, and MobiTrade [13], the authors model opportunistic content transmissions around interests of users, denoted by feeds or channels, respectively. Specifically, the approaches focus on discovery, synchronization, and transport of content [9] and utility-optimal content trading in the presence of non-altruistic users [13].

Both approaches assume an existing network to discover and trade content, namely a pre-defined 802.11 ad-hoc network in [9] and an unspecified network in [13]. In contrast, ICON only establishes networks as a result of matching interests between users in communication range, mitigating the need for prior network coordination and saving energy by deactivating the Wi-Fi interface otherwise. The approaches in [4, 25] propose semantic discovery without the requirement of a pre-defined network structure. However, smartphone operating systems do not yet support the underlying networking functionality, preventing real-world adoption.

Location-based networking. LocP2P [24] leverages location information in a DHT-based content search to reduce query flooding in favor of directed routing paths in mobile multi-hop networks. In contrast, Floating Content [16] and Locus [22] assign a location to each content item and rely on opportunistic interaction between devices to keep content accessible and active. Commercial services, e.g., LoKast [15], rely on pre-existing social network relations between users and facilitate localized discovery, communication, and content exchange exclusively over carrier networks, even between nearby devices.

The presented approaches assume pre-defined application-specific (DTN) networks. We argue that, in addition to the aforementioned energy and efficiency limitations, this restricts the flexibility of real-world opportunistic networking. Approaches solely communicating via carrier networks suffer from a lack of network capacity [8, 14] as well as high energy consumption of the 3G interface (cf. Section 4.3).

Mobile offloading. The increasing load on cellular data networks inspired the augmentation of cellular infrastructures with opportunistic [8] and DTN [14, 17] networks.

ICON shares this motivation. It accounts for the cost and performance limitations by only transmitting interest digests and location updates over carrier networks. Indeed, ICON transmits (large-volume) content solely in opportunistically created 802.11 networks between devices, thereby relieving the carrier infrastructure from large-volume transmissions.

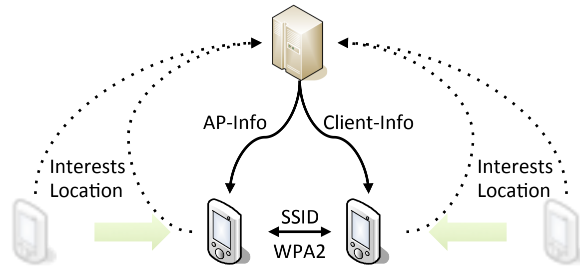

Figure 1: Users indicate their interests, i.e., applications and content, and location to the cloud service. Once users with matching interests report locations within communication range, the service assigns AP and client roles as well as 802.11 parameters for secure, interest-based opportunistic networking.

Cloud-assisted mobile networking. *ParaNets* [26] augments DTN networks with a cloud-based routing solution to leverage up-to-date, global routing information and metrics. *Clone2Clone* [12] even enables interaction between cloned images of mobile devices solely within the cloud to guarantee connectivity and reachability. Conversely, ICON envisions a location-aware cloud-service to facilitate local networking.

3. ICON DESIGN

In ICON, we strive to realize the intuitive notion of opportunistic networking between two users in communication range that have an incentive to do so. We follow a cartesian approach, i.e., build on the available and proven capabilities of smartphones as the main representative of mobile devices. Namely, smartphones can determine their location, natively support spontaneous 802.11 networking in tethered AP mode, and typically come with a mobile data plan. Still, opportunistic networking using 802.11 solely based on location information is insufficient, as users and devices currently have no means to reliably determine a notion of vicinity, network parameters, or incentives to communicate.

In this section, we thus outline the design of ICON (cf. Figure 1) along the questions of *who* users should opportunistically communicate with, *when and where* to establish purposeful networks, and *how* to securely and timely set up an opportunistic 802.11 network between devices. We furthermore propose a versatile content representation tailored to accommodate the diversity of mobile applications and content (*what*). Last, we briefly discuss sensible extensions of ICON and services that become possible.

3.1 Who – Interest-based Networking

Users of multiple, diverse mobile applications [10, 16, 18] currently are unable to match interests and subsequently mediate content exchange in opportunistic, i.e., mobile, uncoordinated, scenarios. In light of the continuing world-wide proliferation of mobile data plans [5] and cheap roaming alternatives [21], we thus facilitate this matching and exchange via a cloud-based service.

Straightforward storage of all application content in the cloud service, subsequent matching, and exchange via cellular networks thereby is infeasible, due to already overloaded carrier networks [8, 14, 17], and inherently costly. Instead, ICON only stores and updates a compact representation of user interests, i.e., as given by his mobile applications as well as requested and provided content, in the cloud service, reducing carrier network transmissions to location updates of negligible size. Comparing user interests for matches, i.e., common applications or provision of requested content, then yields *users with an incentive* for opportunistic networking. However, matching solely on interests does not facilitate *local* opportunistic networking between nearby users as it does not imply physical proximity which would lead to a communication opportunity.

3.2 When and Where – Localized Networking

Opportunistic networking requires users with matching interests to detect whether they are in communication range. Current approaches [4, 11, 23, 25] use periodic 802.11 scans, unsubstantiated by locality or interest information, that incur substantial energy costs and inherently missed opportunities when using duty cycling.

Thus, ICON leverages device locations to only regard users for matches, i.e., their interests, that are within 802.11 communication range. Specifically, storing user locations and interests in a geometry-enabled database allows efficient queries for interests within a given area. Current smartphones thereby offer multiple mechanisms to establish their location, namely via GPS, their current cell ID, or provider-based localization of the observed Wi-Fi networks. To reduce transmission and localization overhead, devices only need to signal their location in case of significant location changes. Likewise, the cloud service only needs to perform a matching within the communication range of signaled reports, instead of continuous querying of the database. We implement two types of location signaling in ICON.

Proactive signaling. Devices periodically signal their location to the cloud service, as for example in Google Latitude [6], if they are moving *and* have a GPS signal, i.e., outdoors. This caters to the intuitive notion of reporting a timely and exact location to facilitate precise matching and utilization of the resulting communication opportunities.

Reactive signaling. Once a device detects no movement for a period of time *or* loses the GPS signal, e.g., indoors, it switches to reactive signaling and reports this to the cloud service. The device then does not update its location but the service queries the device for a location update once a match with its last reported location occurs. The device then reports its location on a best-effort basis, i.e., using the cell ID or Wi-Fi-based localization. As this best-effort approach can not guarantee that two devices actually are in communication range, it entails the risk of unsuccessful connection attempts. ICON thus implements interest matches with reactively reported locations as a user-side option. Once a device regains a GPS signal, it switches back to proactive signaling and notifies the cloud service.

We motivate this distinction with the low energy consumption of current GPS chips[1] in comparison to communication over 3G networks (cf. Section 4.3). As a result, periodically detecting movement and indoor-outdoor transitions via GPS to determine whether to send notifications to the cloud service saves energy.

3.3 How – Mediating/Brokering Networks

To facilitate opportunistic networking between users with matching interests in transmission range, ICON triggers the establishment of a local, high-capacity 802.11 network. To this end, the cloud service *pushes down* to the respective devices i) a random 802.11 SSID for network identification ii) a random WPA2 passphrase for network security and transmission encryption, iii) the 802.11 role of each device, i.e., AP or client, to facilitate the association, and iv) the IP address of each device to mitigate the time overhead of DHCP. Thereby, AP and client roles are randomly assigned to fairly distribute the costs associated with providing 802.11 AP functionality. All communication between clients and the cloud service, i.e., to update location or interest information as well as in network mediation, uses a TLS-encrypted channel and server-side authentication.

ICON realizes the networking functionality by opening a tethered AP with the given SSID on the designated device, assigning the respective IP address, and securing it with the WPA2 passphrase. A timeout value terminates the AP functionality if no association occurs, otherwise the AP device tears down the network once the transmission is finished. On the client side, the ICON app only needs to *scan once* for the given SSID, associates to it, and disassociates after transferring the content. Locality and interest information thereby guarantees a high association success rate and mitigates the costs of periodic 802.11 scans. Subsequently, both parties update their interest digest at the cloud service to keep consistency and enable, for example, dissemination of delay tolerant content [10]. Notably, this process is autonomous but enables the inclusion of alerts or feedback actions, depending on the regarded content (cf. Section 3.5).

3.4 What – Representing Interests

We design ICON to flexibly incorporate arbitrary mobile applications and content. To this end, we represent interests in a two-tiered identifier in which the first tier holds the specific application name, application-specific algorithm, or a pre-defined category for application-independent content. The second tier then identifies interests *within* the scope of the first tier, i.e., within an application or category. Examples are `[mobiclique|<user-id>]`, `[bubblerap|<node-labels>]`, or `[web-content|chants-12-proceedings]`. In addition, application categories, e.g., "dtn", can serve as a first tier while specific application names make up the second tier if no further distinction is required, e.g., `[location-service|floating-content]` in location-based services [16].

When matching interests, we assume users to know their applications and content (categories) of interest, and thus require an exact match on the first identifier tier. The second tier then enables application-specific matching, e.g., perfect matches of social network identifiers and similarity-based matches of web content identifiers (cf. Section 3.5).

3.5 Possible Extensions

In this section, we briefly discuss sensible extensions and usages of the presented basic ICON mechanism.

Partial matches. Computing a normalized similarity score, e.g., the longest prefix match or common subset, of two second tier identifiers A and B allows applications to define sensible thresholds to handle partial matches. For example, a score ≤ 0.65 may denote a non-match, a score ≤ 0.85 triggers a user alert and requires confirmation before establish-

[1] http://www.ifixit.com/Teardown/Samsung+Galaxy+Nexus+Teardown/7182/2
GPS Chip: http://www.csr.com/products/25/sirfstariv-gsd4t

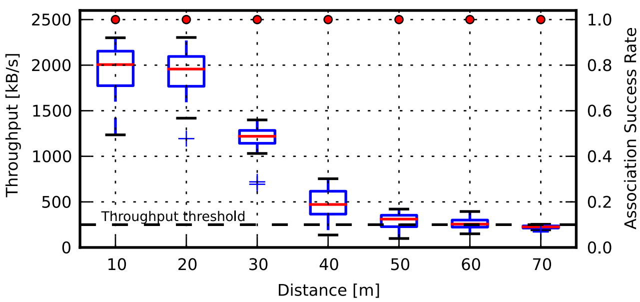

Figure 2: Association success rate and box plot of the throughput in ICON-triggered tethered 802.11 networks over the distance between devices.

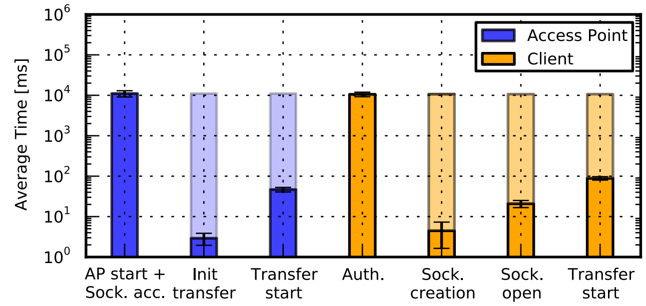

Figure 3: AP-side and client-side proportional timings (solid) of the overall (transparent) 802.11 association time overhead. Note the logarithmic scale.

ing a connection, and a score > 0.85 allows an autonomous 802.11 connection and content exchange.

Multi-party networks. At any given time, multiple devices that share an overlapping set of interest may be in communication range. Restricting network brokering to only one AP and one client device, as described in Section 3.3, would thus prevent the remaining devices from accessing the content immediately and would require subsequent networks for content exchange. The cloud service can thus assign multiple 802.11 clients to an existing or newly created AP network, by extending the signaling to multiple devices.

Interest hiding. Users and application developers need not necessarily trust the cloud service in handling their interests. While infeasible for arbitrary content, well-defined applications can provide an encryption key or a seed to a cryptographic hash function to encrypt identifiers and hide interests towards the service. For well-defined tier one and two identifiers, e.g., user-IDs (tier two) in mobile social networking (tier one), ICON is identifier-agnostic as encrypted or hashed identifiers still allow exact identifier matches. However, encrypted identifiers prevent partial matching.

Trajectory matching. Users can permit the cloud service to derive a movement trajectory and (approximately) predict future locations from the current location and movement. Given the locations (or trajectories) of other users, this enables prediction of interest matches on future locations as well as movement and interaction recommendations, as already proposed for Internet-based approaches [1].

4. EVALUATION

We implemented the client-side functionality of ICON in an Android application, using the native location service to report significant location changes to the cloud service via the 3G connection. We use *Secure WebSockets* to facilitate bi-directional TLS communication between the service and client devices. The cloud service runs a *SpatialLite* database for efficient storage and queries of user interests based on spatial locations. In this section, we thus evaluate the feasibility and performance (Section 4.1), time requirements (Section 4.2), and energy consumption (Section 4.3) of facilitating opportunistic networking in ICON as well as the service performance (Section 4.4).

As smartphones, we use Samsung Galaxy Nexus phones that run Android 4.2.2. We approximate the cloud service with a server running Ubuntu 12.04 that is equipped with a 2.93 GHz quad-core Intel i7 CPU and 4 GB of RAM. Please note that, while we only regard 802.11 in our current prototype, integration of ICON in Bluetooth networking is possible by assigning piconet roles and a network PIN.

4.1 Feasibility

We evaluate the feasibility of client-side opportunistic networking in ICON by measuring both the success rate and the throughput of tethered AP associations, as triggered by the cloud service, with regard to the distance between the smartphones. In this, we first highlight the general performance of exchanging (application) content in local 802.11 networks. Second, we strive to find a sensible range around a device location in which the cloud service should report matchings to trigger 802.11 networking with both a sufficient association success rate and transmission throughput.

We thus measured the achieved **throughput** in transmitting a 5 MB file 30 times at line-of-sight for each distance as well as the success rate of attempted associations. As Figure 2 shows, transmissions in the network achieved a net throughput of up to 2 MB/s. Also, while the throughput in the network decreases with increasing distance, we observe an association rate of 100 % at all distances. We set a throughput of 250 kB/s as a lower bound for sensible network performance, and find that transmissions over 60 m satisfy this threshold while 70 m only allow 223 kB/s.

Selecting a **range** for interests matching thus entails a tradeoff between the achievable throughput and the number of communication opportunities. Assuming a GPS localization accuracy of $\pm$ 10 m we regard a range of 40 m as sensible, allowing an average throughput of 488 kB/s. Worst-case deviations in the localization accuracy at both devices then still affords a network throughput of 264 kB/s at 60 m.

However, diverging applications requirements may emphasize different network characteristics, suggesting the inclusion of another criterium for interest matching. For example, a DTN or location-based application with small message sizes may tolerate lower throughput for an increase in coverage and communication opportunities that is provided by a larger range. Conversely, data-dependent applications, e.g., pictures and videos in mobile social networking, may value a low number of high-performance links between devices higher than a larger number of links with less throughput. User interests may thus carry an additional flag that indicates a preference of network characteristics, to be regarded in the matching process.

4.2 Time Overhead

In mobile scenarios, the time overhead of establishing an association can affect the ability to communicate within the

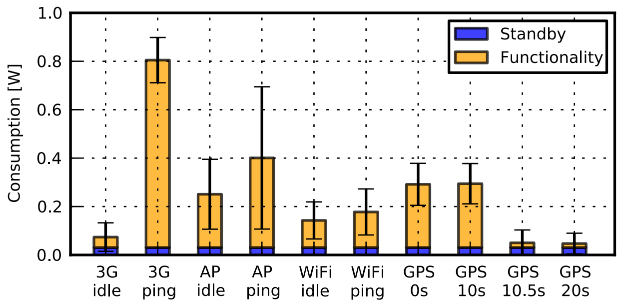

Figure 4: Energy consumption of smartphone functionalities as utilized in ICON.

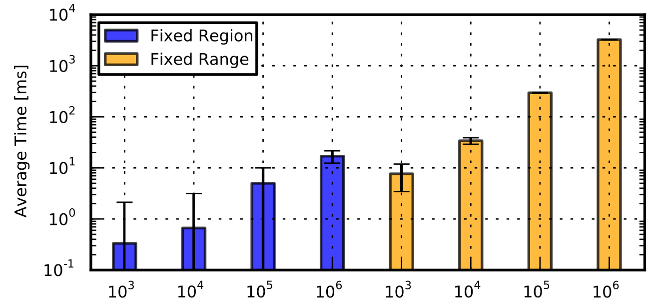

Figure 5: Query response times for increasing populations of a fixed region (left) and the range around a user location. Please note the logarithmic scale.

respective contact duration. We thus briefly evaluate the time factor of triggering 802.11 networks in ICON. Figure 3 shows the average timings over 30 runs for 802.11 AP (left side) and client functionality after the cloud service triggers 802.11 networking. In total, establishing a triggered association and transferring a 1 Byte payload for completeness takes about 10 s. Of this, the 802.11 association process, including scanning for the indicated network, consumes the majority of time, as evident in the share of "AP start" and "Authenticated" states. With regard to contact durations in realistic scenarios [20], this leaves the vast majority of contacts usable for communication of payload.

4.3 Energy Consumption

ICON emphasizes purpose-driven 802.11 networking based on user-reported locations over 3G communication. We strive for minimization of traffic sent over carrier networks as well as preservation of battery life. In this section, we thus evaluate the sensibility of our design with regard to the energy consumption of the employed components, namely the GPS module, the 3G interface, and the 802.11 interface.

To this end, we place a low-resistance shunt (82 mOhm) between the fully loaded battery and the power connector of the smartphone. We measure the actual current drained from the battery as the potential over the shunt using a Tektronix TDS 2024B oscilloscope to allow for time-continuous measurements. To measure the respective energy consumption, we turned off the screen, other components, and applications and conducted 5 runs of 100 s for each component.

Figure 4 thus shows the average energy consumption of the 3G (HSDPA) and Wi-Fi interface in idle mode and when continuously sending ping messages as well the consumption of the GPS interface when requesting a position update continuously and every 10 s, 10.5 s, and 20 s. We also highlight the system standby energy consumption for comparison.

With regard to the **energy consumption of wireless communication**, the results support our design of offloading actual transmissions in purpose-driven 802.11 networks. Sending data over the 3G interface requires more than four times the energy of communicating as an 802.11 client (Wi-Fi ping) and twice the energy of communicating while operating an AP[2]. In turn, maintaining an active 802.11 AP or client interface, as required for discovery approaches that base on continuous 802.11 scans, consumes more energy in idle mode than an idle 3G interface. As such, deactivating the 802.11 interface in favor of an idle 3G interface to only purposefully trigger activation of the 802.11 interface further reduces the energy consumption. Since mobile users typically maintain their 3G connection continuously, we believe that ICON does not add energy consumption in general, while enabling opportunistic networking at the minimal additional cost of location updates.

To evaluate this **localization cost** in terms of energy[3], we measured the required energy of requesting timely location updates in order to allow for precise location and interest matching. Figure 4 shows the high cost of requesting continuous updates (GPS 0s), in contrast to the minimal amount of energy required to update the location every 20 s (GPS 20s). Assuming a pedestrian mobility with a velocity of 1.5 m/s, a 20 s update interval would allow a localization every 30 m, a distance that is well covered by the range of tethered AP networks (cf. Section 4.1). In contrast, an update interval of 10 s (GPS 10s) results in a notably increased energy consumption that is almost equal to the costs of continuous updating. This is because the update interval, as registered by the application, is compared to the Android-native `GPS_POLLING_THRESHOLD_INTERNAL` parameter that governs for which intervals the GPS module may be switched off. Per default, this parameter is set to 10 s, update intervals $\leq$ 10 s thus result in the GPS module being permanently active and unable to preserve energy. The significant reduction of a 10.5 s update interval (GPS 10.5s) (15 m) thereby highlights the impact of this parameter and the possible gains in preserved energy.

4.4 Cloud Service Evaluation

ICON relies on the cloud service to manage user locations and to match users in communication range based on their interests and locations. We thus evaluate the query response times for population densities between 10^3 and 10^6 in a fixed size region[4] of 1.8 km^2 and in the 40 m range around a user location in a *SpatialLite* database. To this end, we insert random locations in the region and in the range, respectively, and query for matches to derive users of matching interests.

Figure 3 shows the average response time of 30 queries for each number of locations. The results thereby support the performance of spatial user management and motivate an elastic scaling of region sizes, with one machine instance in the cloud managing one region, to the current population density to avoid overload situations and high response times.

5. CONCLUSION

[2]AP tethering in Android requires an (idle) 3G connection, the energy consumption is included in AP measurements.

[3]Currently, a location update message requires 96 Bytes.

[4]Approximately the city center area of Aachen.

In this paper, we proposed ICON, a platform to enable opportunistic networking of heterogeneous applications and content. Building on a mobile cloud solution for interests matching, ICON triggers purposeful 802.11 opportunistic network associations based on the location and communication range of a user. Providing 802.11 security credentials furthermore alleviates the traditionally difficult task of establishing keys in a distributed system and affords WPA2-secure networking and content exchanges. Such networking based on interests and locations alleviates the need for repeated 802.11 network scans and associations and the associated expenses in energy, time, and user interaction. In contrast, ICON builds on one-time indication of applications and content of interests to enable purpose-driven local 802.11 associations and content exchange autonomously or based on user-definable similarity thresholds.

Our evaluation of ICON shows the feasibility, timeliness, and performance of triggered 802.11 networks at sufficient ranges, i.e., distances between the participating devices. Furthermore, our preliminary energy consumption measurements show the benefits of deactivating the 802.11 interface in favor of low-volume usage of the 3G interface to discover users and devices of interests as well as mediate 802.11 networks. Conversely, the lower energy consumption of data transmissions in 802.11 networks compared to 3G networks supports our design of purposefully establishing a local 802.11 network between matching users.

5.1 Discussion

We envision multiple services to become possible when using our basic ICON design as a building block. Associating credits and popularity scores with (public or web) content allows micro-payment and incentive schemes. Notably, such schemes can help opportunistic applications reach a critical mass and sustain operation. In contrast to fully distributed approaches, managing scores, credits, and receipts in the cloud service makes such schemes more readily applicable.

To build on ICON, applications only need to maintain their respective list of interests, i.e., publishing, requesting, and if necessary updating interests specific to the application. While ICON natively facilitates simple content transfer between devices, more sophisticated application functionality may be triggered by ICON by alerting the respective application (or the user) once a network for the respective (application-specific) interest is established.

5.2 Outlook

Given a location-aware cloud service, a main priority of future work is ensuring the location privacy and anonymity of users. Although interest hiding might prevent usage profiling, storing user locations entails the possibility of location tracking, discouraging the adoption by users. Future work will thus focus on incorporating proven anonymity [7] and location privacy [2] approaches.

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6. REFERENCES

[1] S. Amini, A. Brush, J. Krumm, J. Teevan, and A. Karlson. Trajectory-aware mobile search. In *CHI*, 2012.

[2] S. Amini, J. Lindqvist, J. Hong, J. Lin, E. Toch, and N. Sadeh. Caché: caching location-enhanced content to improve user privacy. In *MobiSys*, 2011.

[3] M. Bakht, M. Trower, and R. H. Kravets. Searchlight: won't you be my neighbor? In *MobiCom*, 2012.

[4] J. A. Bitsch Link, C. Wollgarten, S. Schupp, and K. Wehrle. Perfect difference sets for neighbor discovery: energy efficient and fair. In *ExtremeCom*, 2011.

[5] CISCO. Global mobile data traffic forecast, 2012-2017. `https://communities.cisco.com/docs/DOC-32557`.

[6] Google. Latitude. `http://www.google.com/latitude`.

[7] M. Gruteser and D. Grunwald. Anonymous usage of location-based services through spatial and temporal cloaking. In *MobiSys*, 2003.

[8] B. Han, P. Hui, V. A. Kumar, M. V. Marathe, G. Pei, and A. Srinivasan. Cellular traffic offloading through opportunistic communications: a case study. In *CHANTS*, 2010.

[9] O. R. Helgason, E. A. Yavuz, S. T. Kouyoumdjieva, L. Pajevic, and G. Karlsson. A mobile peer-to-peer system for opportunistic content-centric networking. In *MobiHeld*, 2010.

[10] P. Hui, J. Crowcroft, and E. Yoneki. Bubble rap: social-based forwarding in delay tolerant networks. In *MobiHoc*, 2008.

[11] T. Kärkkäinen, M. Pitkänen, and J. Ott. Enabling ad-hoc-style communication in public wlan hot-spots. In *CHANTS*, 2012.

[12] S. Kosta, V. C. Perta, J. Stefa, P. Hui, and A. Mei. Clone2clone (c2c): Peer-to-peer networking of smartphones on the cloud. In *HoTCloud*, 2013.

[13] A. Krifa, C. Barakat, and T. Spyropoulos. Mobitrade: trading content in disruption tolerant networks. In *CHANTS*, 2011.

[14] Y. Li, G. Su, P. Hui, D. Jin, L. Su, and L. Zeng. Multiple mobile data offloading through delay tolerant networks. In *CHANTS*, 2011.

[15] LoKast. Interactive spaces. `http://www.lokast.com/`.

[16] J. Ott, E. Hyytia, P. Lassila, T. Vaegs, and J. Kangasharju. Floating content: Information sharing in urban areas. In *PerCom*, 2011.

[17] A. Petz, A. Lindgren, P. Hui, and C. Julien. Madserver: a server architecture for mobile advanced delivery. In *CHANTS*, 2012.

[18] A.-K. Pietiläinen, E. Oliver, J. LeBrun, G. Varghese, and C. Diot. Mobiclique: middleware for mobile social networking. In *WOSN*, 2009.

[19] M. Pitkanen, T. Karkkainen, J. Greifenberg, and J. Ott. Searching for content in mobile dtns. In *PerCom*, 2009.

[20] M. Pitkanen, T. Karkkainen, and J. Ott. Mobility and service discovery in opportunistic networks. In *PerCom Workshops*, 2012.

[21] T-Mobile. Prepaid data plans. `http://prepaid-phones.t-mobile.com/prepaid-plans`.

[22] N. Thompson, R. Crepaldi, and R. Kravets. Locus: a location-based data overlay for disruption-tolerant networks. In *CHANTS*, 2010.

[23] S. Trifunovic, B. Distl, D. Schatzmann, and F. Legendre. Wifi-opp: ad-hoc-less opportunistic networking. In *CHANTS*, 2011.

[24] Y.-C. Tung and K.-J. Lin. Location-assisted energy-efficient content search for mobile peer-to-peer networks. In *PerCom Workshops*, 2011.

[25] H. Wirtz, D. Martin, B. Grap, and K. Wehrle. Demo: On-demand content-centric wireless networking. In *MobiCom*, 2012.

[26] M. P. Wittie, K. A. Harras, K. C. Almeroth, and E. M. Belding-Royer. On the implications of routing metric staleness in delay tolerant networks. *Computer Communications*, 2009.