Could Message Ferrying be a Viable Technology for Small Cell Backhaul?

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Abstract

Small cell is seen as key to combat the looming capacity crisis in next generation mobile networks. Backhaul, however, is proving very costly, especially when it comes to connecting outdoor small cells to the core network. We analyse the viability of message ferrying as a low-cost option for small cell backhaul. The idea is that the smartphones of vehicle occupants could work as an army of ferries to transfer data between a small cell and another location that already has an existing backhaul infrastructure. We analyse the potential capacity of ferry-based backhaul using real road traffic data and the capacity of two different types of phone storage, RAM and internal memory. We find that even with only a 5% use of the phone storage, message ferrying could deliver giga bits per second capacity and transfer tens of peta bytes per week. Our analysis also reveals that the choice of storage type, which may be influenced by privacy concerns, has a significant effect on capacity. Operators choosing to use the internal memory can expect to increase the ferrying capacity by nearly an order of magnitude compared to a RAM-only solution.

1 Introduction

To meet the exponential growth in mobile data traffic, cellular network operators are deploying new radio cells using small form-factor short-range base stations often mounted on existing street furnitures, such as lamp posts and bus stops. Due to their short-range and small size, these are called *small cells*, while the existing traditional cells with a longer range base stations mounted on the rooftops or radio towers are referred to as *macro cells*. The existing macro cells will continue to deliver wide area mobility services, such as mobile phone calls, but the small cells are seen as pivotal to support the high data rate services, such as video streaming, demanded at numerous urban hot spots. Although small cell deployment is still in its early stage, according to some predictions, small cells will make up 90% of all base stations by 2016 [10] and there could be 11.5 million small cells by 2018 [4].

To meet the demand effectively, operators would need to deploy the small cells where they are needed the most, i.e., in traffic hot spots, which not necessarily be the locations where the operators have existing backhaul infrastructure. This is creating a looming backhaul crisis for the next generation mobile networks. Although there exists a plethora of backhaul technologies, such as fibre, microwave, millimeter wave, free space optics, satellite, or leased lines, they would be too costly for a small cell, which carries only a fraction of the total volume carried by a macro cell. Given that many hot spots may appear and disappear dynamically, it would be harder to recover any capital investments for these small cell backhauls. Due to these difficulties, backhaul is currently considered a major obstacle to the large scale deployment of small cells. Indeed, a recent survey has found that "56% of operators cite backhaul as one of the greatest challenges, second only to fundamental issues of site acquisition" [10].

At the moment, the industry does not have a clear roadmap for solving the backhaul crisis, which is expected to worsen in the future as the demand continues to grow exponentially. This has created a need for thinking *outside the box* for any viable concept that has the potential to carry backhaul traffic at a significantly lower cost than existing options. In this report, we put *message ferrying* under the spotlight and examine its viability as a potential backhaul technology for small cells.

2 Motivation for Message Ferrying

Message ferrying [11] is a concept of achieving data communication by means of physically carrying (ferrying) data between nodes using special mobile nodes (ferries). The ferries can be specially built robots, cars, unmanned aerial vehicle (UAV), or any other mobile device. Message ferrying is particularly useful in challenging situations where it is difficult, costly, or not possible, to establish an end-to-end communication link between two nodes. Past applications of message ferrying include providing basic Internet access to remote villages in developing nations [7], reducing energy cost of battery-operated environment monitoring sensor nodes [1], and restoring connectivity between partitioned mobile nodes in a military field [3, 12].

There are two abundant resources in the cellular eco-system motivating the

Table 2.1: Storage capacity (in GB) for smartphones from different manufacturers as of 2014. If these capacities quadruple, the average RAM and internal storage could reach 8GB and 64GB, respectively, by 2017.

Smartphone	RAM	Internal	Removable
Samsung S4 4G	2	16	64
Samsung Galaxy Note 3	3	32	64
iPhone 5S	1	64	None
HTC One 4G 801S	2	64	None
HTC Desire 600	1	8	64
Sony Xperia Z 4G	2	16	32
Sony Xperia Z 4G	2	16	64

potential application of message ferrying to small cell backhaul problem:

- Abundance of short-range high capacity local spectrum within small cells. Early small cell deployments are using the same low frequency (below GHz) spectrum used for the macro cells, which is costly and offers limited data rates. Spectrum authorities, however, are planning to release significant new high frequency (above GHz) spectrum, which is currently underutilized, for small cell use at an exceptionally low licensing cost [8]. At the same time, there have been some recent breakthroughs that will soon allow mobile devices to transmit and receive data at an extraordinarily high rate for a short distance using frequency bands in the range of hundreds of GHz to terahertz [6]. Finally, there is a move to develop a new base station technology [8] that can efficiently use the existing unlicensed bands, such as the ones used by WiFi and radars, which are totally free of cost. These developments suggest that availability of high capacity short range spectrum for local radio access within the small cell is unlikely to be an issue in the future.

- Storage abundance in smartphones. Storage cost has fallen drastically in the recent years fueling large storage capacity in smartphones. While early smartphones could barely store more than a few kilo bytes in the main memory, today's smartphones are shipped with at least 1GB of RAM with an additional 8-64 GB of *internal* and a further 32-64 GB of *removable* storage, such as SD and microSD cards. Table 2.1 shows the storage capacity available in smartphones from different manufacturers as of 2014. These numbers will quadruple by 2017 if we apply Moore's law of doubling in every 18 months. This trend suggests that in the future, storage in mobile devices will be considered an abundant resource open to exploitation by novel applications.

Figure 2.1 shows how the local spectral and storage abundance could be exploited to realise a ferry-based backhaul for a small cell. Imagine that a hot spot has been recently identified at a public park where the operator has no existing backhaul service available to connect the small cell to its core network. However, the operator does have a high capacity backhaul down the road as part of its existing infrastructure to connect its macro cells. The operator decides to use some of its limited long-range spectrum only to transfer the delay-sensitive

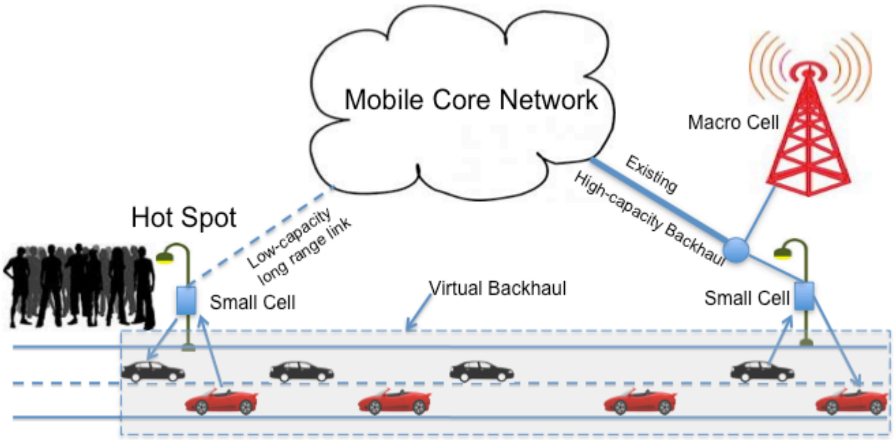

Figure 2.1: A virtual ferry-based backhaul is created when motorists with smartphones ferry data between hot spot and existing backhaul infrastructure.

data between the hot spot and the core network. To transfer the rest of the data, the operator deploys another small cell where it has high-capacity backhaul (the small cell at the right). It then uses the mobile devices, such as smartphones carried by the occupants of cars, that travel between these two small cells to ferry data between the hot spot and the existing backhaul and eventually the core network, realising a ferry-based virtual backhaul.

A ferry-based backhaul as depicted in Figure 2.1 would have the following important advantages against the existing backhaul solutions:

- Ultra-low-cost: The ferry service could be completely free. It enjoys zero capex, because it neither requires installation of any equipment at each cell site, nor running of any fibre or cable. It also has a zero opex, as there is no power supply, no leasing and no licensing cost of long-range spectrum (it only uses *unused* local spectrum and device storage for pushing data in and out of moving smartphones). Finally, it uses the in-situ road traffic avoiding any cost associated with special-purpose ferries.
- Ultra-fast deployment: It is available immediately compared to long setup time of existing backhaul options.

3 Viability

We analyse the viability of ferry-based backhaul by examining a range of practical issues including capacity, delay, privacy, energy consumption, and user acceptability.

3.1 Capacity

How much data the operators can realistically offload to a ferry-based backhaul? Assuming that there is plenty of local bandwidth available in the small cell to transfer data to and from passing smartphones, the capacity of ferry-based backhaul is basically the product of the frequency of ferries and the available storage in those ferries. Since ferries are the smartphones carried by the motorists, vehicular traffic on the road plays a critical role in determining the backhaul capacity. To derive the capacity, we use the following notations:

- V_p: Traffic volume of mobile phones subscribed to the operator measured in number of phones passing through a fixed point of the road in an hour
- V_c: Traffic volume of cars measured in number of cars passing through a fixed point of the road in an hour
- s: Average storage capacity of phones on the road in GB
- α: Average number of occupants per car
- β: Market share of the operator measured as a fraction of all subscriptions in the region
- γ: Phone storage utilisation

Phone storage utilisation (γ) defines the average utilisation of the storage capacity available to the user. For example, $\gamma = 0.9$ means that on average, the storage will be 90% full leaving only 10% to be utilised by the ferry-based backhaul. We obtain the capacity of ferry-based backhaul as:

$$C = \frac{V_p}{3600} \times s \times 8 \times (1 - \gamma) \; Gbps \tag{3.1}$$

where $V_p = V_c \times \alpha \times \beta$. For an $\alpha = 1.5$, $\beta = 0.4$, and $\gamma = 0.95$, we have:

$$C = V_c \times s \times 0.067 \; Mbps \tag{3.2}$$

We see that, for a given traffic volume, capacity of ferry-based backhaul will be significantly influenced by the choice of storage type. For example, the storage capacity is either 8 GB or 72 GB (2017 projections) depending on whether the operator wants to use only RAM for stronger privacy protection or employs both RAM as well as internal storage for greater capacity. In this case, a 9× capacity increase is possible by choosing to use the internal storage for data ferrying.

Once the decision is made about the type of storage used for data ferrying, the vehicular traffic volume (V_c) will directly limit the achievable capacity of a ferry-based backhaul. As part of their transport capacity planning, road and transport authorities routinely measure traffic volume at different road locations. Figure 3.1 shows the hourly volume for three different urban roads in Sydney. We see that vehicular volume varies significantly during the 24 hours generally peaking during the day. The corresponding capacity graphs for Monday traffic are shown in Figure 3.2. As expected, we find that capacity can be increased by nearly an order of magnitude by considering the internal storage

Table 3.1: Ferrying capacity in terms of weekly volume of data carried by Sydney traffic for an average RAM of 8 GB per phone.

Road	Weekly Traffic	Data (Peta Byte)
Paramatta Road	208,712	50
Cleveland Street	142,585	34
Enmore Road	91,182	21

of the phone. Ferrying capacity in terms of weekly volume of data carried by Sydney traffic is shown in Table 3.1.

Based on the Sydney traffic, we find that message ferrying could realise a very high capacity backhaul. Using only 5% of the phone storage for data ferrying ($\gamma = 0.95$), we could achieve a ferrying capacity in the order of Gbps and tens of peta bytes per week even if the operator uses only RAM. Use of internal storage would increase these capacities to 10 Gbps and hundreds of peta bytes per week. Of course, to realise these capacities, the small cell base station would also need such high bandwidth to transfer the data to the passing phones. With current technology, the data rates available for small cell base stations may be the bottleneck and limit the exploitation of the full ferrying potential. However, researchers believe that in the future, terahertz communication may be utilised to transfer data at 100 Gbps to Tbps over a *short distance* [2], which perfectly suits small cells. Developments of such extremely high capacity short-range communication systems are expected to pave the way for exploiting the full potential of ferry-based backhaul.

Our calculations assumed that all cars, given by the traffic volume at a point, will travel from a small cell to another. In reality, there is a possibility of a car exiting the road between two small cells. However, for capacity calculation, this can be incorporated in one of the discounting factors, α, β, or γ. A more serious issue with disappearing cars is the reliability of data transfer, which we consider as a key challenge for ferry-based backhaul (see Section 4).

3.2 Delay

High delay is a characteristic feature of message ferrying as data is physically carried by the ferries. Despite this delay, ferry-based backhaul would be appropriate for uploading photos and videos to online social sites, as these are not strictly delay-sensitive. As a matter of fact, given the increasing size of the multimedia objects, the delay could be competitive with some of the low-capacity wireless backhaul links. For example, a vehicle travelling at 60 km/h on an urban road could ferry a 5MB photo to the core located 1 km down the road in just 60 seconds, which is faster than a direct wireless backhaul of capacity 512 Kbps.

In general, the delay factor could be overcome through the simultaneous use of the macro link as follows. Small cells located within macro cell coverage can be directly backhauled by connecting the small cell base station (BS) to the macro cell BS using a small allocation of the macro cell spectrum. This would be a low capacity link to be used only for delay-sensitive traffic, such voice calls, web browsing, or other control information such as transmission of user (client)

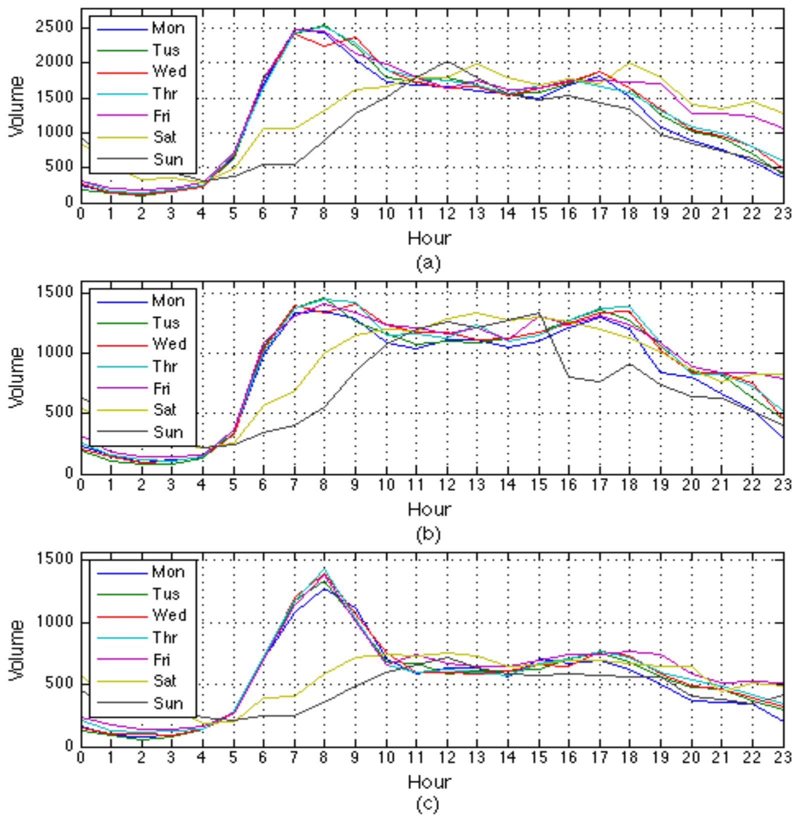

Figure 3.1: Hourly traffic volume for (a) Paramatta Road Eastbound (Station 02.273.E), (b) Cleveland Street Eastbound (Station 02.038.E), and (c) Enmore Road Northbound (Station 02.062.N) collected during the week commencing 15 August 2005 (Source: Roads and Maritime Services, Sydney, Australia [9]).

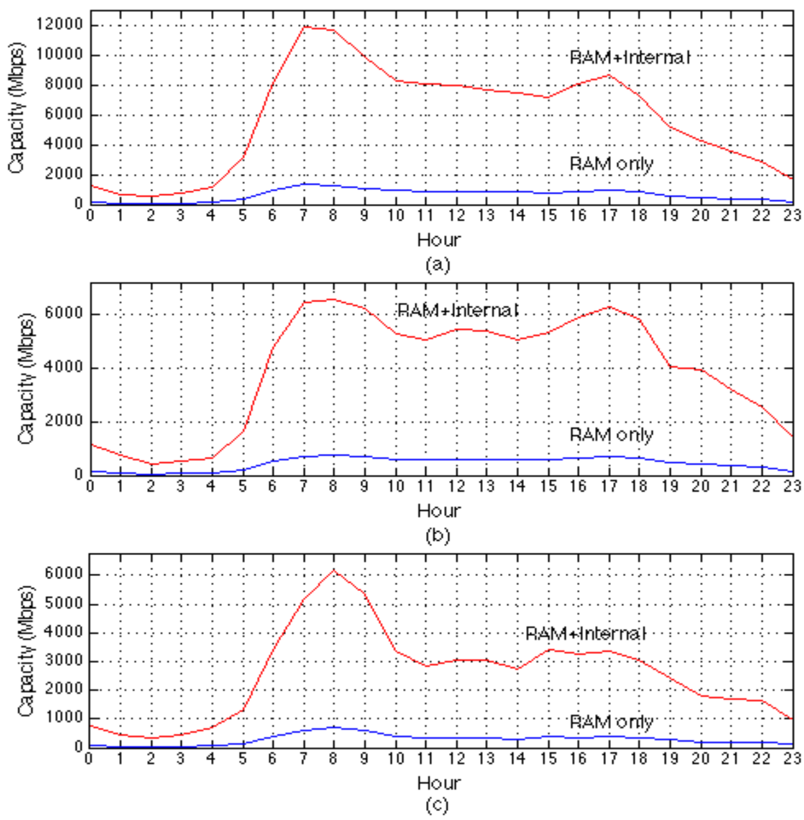

Figure 3.2: Capacity of ferry-based backhaul as a function of hour-of-day for (a) Paramatta Road Eastbound (Station 02.273.E), (b) Cleveland Street Eastbound (Station 02.038.E), and (c) Enmore Road Northbound (Station 02.062.N) based on traffic volume data of 15 August 2006.

request to Internet servers.

With the low-delay macro link in operation, a large fraction of real-time data can still be ferried to and from the small cell. For example, to support video streaming, client requests can be immediately sent to the content server over the macro link. The first few seconds of video may have to be downloaded to the client buffer over the macro link to minimise launching delay, but the rest of the video could be streamed over the ferries as the client would only need new data "chunks" at periodic intervals. Assuming users watch video streaming that are not too short, a significantly higher percentage of the watched video would be transported over the ferry-based link compared to the macro link.

Similarly, when downloading a file, the request for the file could be sent immediately over the macro link and the file itself could be ferried to the client. The larger the file, the less noticeable it comes to the user that the file is ferried, because files of different sizes that fit in the same ferry will take the same amount of time to reach the destination. Therefore, overall user quality of experience (QoE) could be improved by off loading large file transfers to the ferry-based backhaul.

3.3 Privacy

Because the user data will be temporarily stored in third party devices, we need to analyse the risk to privacy and security. Basically, we need to establish how easy or difficult it is for the user to access the backhaul data stored in the device.

There are three different types of storage in a mobile phone, RAM, internal, and removable. Given that the user has direct access to internal and removable storage for storing and retrieving personal data or files, they pose a greater privacy risk compared to RAM, which is accessed only by the CPU. Between internal and removable, it would be riskier to store in the removal storage due to the fact that the user can remove it at any time, while the internal storage is built into the phone hardware.

The most significant argument in favour of privacy, however, would be the fact that the device-to-base-station control system actually uses a *dedicated* processor and operating system (OS) [5] on the mobile device that are separate from the CPU and OS used by the user apps. This hardware separation would make it significantly harder, if not impossible, for the users to access any backhaul data carried in their devices. To make it even safer, the storage could be even partitioned between these two CPU/OS. Finally, data could be encrypted for the ultimate privacy if required.

3.4 Energy consumption

Storing and retrieving data would consume some battery energy of the smartphone. However, because all store/retrieve happens within the small cell coverage using a significantly lower power (compared to macro cells), battery consumption would be minimal. Battery consumption can be further limited by not selecting the same smartphone as a data ferry more than a target number of times within a 24 hour period. Another strategy could be to select the smartphones with high residual battery energy with higher priority.

3.5 User acceptance

There may be issues with the user accepting the fact that their personal devices are being used by the network for temporary storage of network traffic. However, this could be addressed through various forms of incentives, including offering a larger data plan to those who agrees to ferry backhaul data.

4 Challenges

The main challenge will be providing high reliability as expected from any backhaul service. Previous work on message ferrying [12] relied on special controllable ferries, which is not applicable for the ferry-based backhaul as illustrated in Figure 2.1. The cars on the roads are the ferries and mobile operators have no control over their mobility. Traffic congestion and unpredictable vehicle mobility will, therefore, directly interfere with the data transmission. For example, a vehicle exiting the road before reaching the intended data drop off point will cause an eventual loss of data. Similarly, a car carrying part of a video stream may suddenly stop at a traffic light, risking a “frozen” video at the destination small cell. It may be possible to improve reliability through redundancy, i.e., copying the same data in multiple phones. However, redundancy will reduce usable capacity and it is not clear whether there is any limit to reliability improvement that can be achieved through redundancy.

5 Conclusion

We have discussed the motivations for considering message ferrying as a low-cost alternative to small cell backhaul. Our analysis shows that ferry-based backhaul could support high capacity, preserve privacy of user data, limit energy consumption of mobile devices, and attract user acceptance. However, the key unknown is *reliability*, which is particularly challenging given that data is to be ferried by smartphones inside the cars, whose mobility cannot be controlled. Whether redundancy or other type of error correction can achieve the target reliability without sacrificing significant capacity is a topic of further investigation.

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