RICE UNIVERSITY

Small Cells and Mobile Clients: a Measurement Study of an Operational Network

by

Sharan Naribole

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APPROVED, THESIS COMMITTEE:

Dr. Edward W. Knightly, Chair
Professor of Electrical and Computer Engineering

Dr. Behnaam Aazhang
J.S. Abercrombie Professor of Electrical and Computer Engineering

Dr. Lin Zhong
Professor of Electrical and Computer Engineering

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ABSTRACT

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Small cells address the increasing traffic demands from mobile users and target improved coverage and capacity and better quality of experience to users. This thesis presents the first large-scale measurement study of voice and data service performance of an operational small cell cellular network. Nation-wide fine-grained voice service measurements are analyzed to gain insight into the nature and implications of handovers on voice service performance. A new statistical correlation framework to find the statistical dependency between two events across multiple cells is proposed. The effectiveness of the proposed framework is demonstrated using data service quality measurements of a relatively higher traffic demand location. This in-depth study targets a better understanding of the advantages and trade-offs of deploying small cells in operational networks and provides a foundation for future studies of mobility management and development of techniques for improvement of service performance.
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A key technology to address the rapidly growing demand for mobile data is the deployment of small cells overlaid by the traditional macro cellular network. Macro cells provide blanket coverage whereas small cells infuse additional capacity at traffic hotzones and improve coverage. Due to lower transmission power and reduced height, the coverage areas of small cells are significantly less than macro cells.

Despite their potential performance benefits, operators are facing new technical challenges mainly in mobility management [2, 3]. Handovers are needed to maintain connectivity of a mobile user. The expected number of handovers during a call is likely to increase with small cell deployment. Simulation studies [15] have shown a 120% - 140% increase in handovers for a naive small cell deployment setting. From the network point of view, the increase in handovers leads to an increase in the control signaling load for eg. to the core network. None of the existing works have analysed the increase in handovers for a data-driven/ usage based small cell deployment.

Not only is there an increase in number of handovers but also the likelihood of handover failure due to much smaller coverage area of the small cells. The challenges of small cells include abrupt cell boundaries [4], increased neighboring cells list [5] and too early handover triggers caused by range expansion [6]. Current cellular standards
contain radio link re-establishment mechanisms to prevent call from getting dropped even after occurrence of handover failure. However, there is no prior work on actual call drop analysis for small cell deployments overlaid by macro cells.

Cellular operators have started deploying small cells with a focus on locations with relatively higher traffic demand. The network operations team conducts manual field trials at individual sites for performance evaluation. However, these trials are highly dependent on local traffic patterns and wireless channel characteristics. A large-scale assessment of small cells independent of such local patterns is needed.

This paper presents the first large-scale measurement study of voice service performance of an operational small cell cellular network. We use a vast data set from the cellular service provider’s operations that includes performance counters at the cell towers, anonymized call detail records (CDR) and network topological information.

To study voice services, we utilize nation-wide fine-grained voice service measurements for calls that involve at-least one small cell over their trajectory. The measurements are collected over 14 days comprising over 500,000 calls and over 1,500 small cells. We analyze the data to gain insight into the nature and implications of the handovers on the service quality experienced by the users.

The contributions of this thesis are as follows:

**Number of Handovers.** We expect the number of handovers will increase with the deployment of small cells. However, we find a significant percentage (84.7%) of answered calls do not involve any handovers and thus, originate and terminate at the same small cell.

**Extra Handovers.** We find that 74.5% of the calls that have one or more handovers with small cell deployment would have no handover in a macro only network. Surprisingly, all of these calls have just one extra handover introduced by small cell deployment. We analyze the relationship between the relative percentage increase in
handovers due to small cell deployment and the number of handovers that would take place without small cells. We find that for a user with high number of handovers in a macro only network, the relative increase in handovers due to small cells is negligible.

**Call Drop Analysis.** We define a call involving handovers as a *mobile call*. We find the call drop probability is the highest for a mobile call terminating in a small cell independent of the call duration. This finding can be attributed to the abrupt cell boundaries of the small cells.

To study *data services*, we utilize hourly coarse-grained measurements collected at small cells and macro cells. The measurements are collected over period of three months. We focus on a tourist location having a relatively higher traffic demand and user mobility. To address the demand, the service provider has deployed a relatively higher number of small cells in the location per unit area. A total of 53 small cells and 5 macro cells were selected for the study. We analyze the traffic offloaded to the small cells and the impact of potential factors that can disrupt the service quality requested by the users. We employ *retainability* as a service performance metric as it reflects successful termination as issued by the user. For data services, our contributions are as follows:

**Traffic Offload.** We find the percentage of traffic offload to small cells to be as large as 50.4%, a significant fraction of the total traffic load. We find the macro cell traffic and small cell traffic have a significant positive correlation indicating the positive impact of small cell deployment in reducing the likelihood of macro cells entering the state of traffic congestion.

**Statistical Correlation Framework.** We propose a new statistical correlation framework to find the spatial statistical dependency between two service quality metrics across multiple small cells. We demonstrate the effectiveness of our framework through operational case studies.
The remainder of this thesis is organized as follows. In Chapter 2, we discuss the handover procedure and challenges introduced by small cell deployment. In Chapter 3 and Chapter 4, we provide detailed performance analysis of voice service and data service respectively. Chapter 5 reviews related work and the paper is concluded in Chapter 6.
In Section 2.1, we provide a brief overview of the heterogeneous cellular network architecture consisting of both small cells and macro cells. In Section 2.2, we introduce the handover procedure and the different types of handovers in a heterogeneous cellular network. In Section 2.3, we outline the challenges for managing user mobility and handovers within small cells and between small cells and macro cells.

2.1 Cellular Network Architecture

Figure 2.1 shows the UMTS cellular network architecture and the logical connections established between the different domains of the network. The User Equipment (UE), Radio Access Network (RAN) and Core Network (CN) form the three domains of cellular network. The UE or mobile device communicates using the air interface to the RAN network. The UE can either connect to a small cell or a macro cell depending on signal strengths, available network capacity and traffic demand. The data traffic is exchanged between UE and CN in Packet Switched (PS) mode and voice traffic is exchanged between UE and CN in the Circuit Switched (CS) mode.

The UE can exchange traffic with the network only after a Radio Access Bearer
(RAB) is established with the CN. This procedure starts with the UE establishing a Radio Resource Control (RRC) connection with the Radio Network Controller (RNC). The three most common types of RRC failures observed are: poor RF channel quality, denials for radio link addition in soft handovers and blocking when all available RAB connections are assigned to existing users [7]. If the RNC accepts the RRC connection request, it sends a positive reply to the UE and a SRB request to the core network. Once the SRB (Signaling Radio Bearer) is successfully established between the RAN and CN, the CN establishes a Radio Access Bearer towards the UE. This is achieved by sending a RAB establishment request message that includes RAB identifier, QoS profile and transport layer addressing. Once the UE indicates a positive response to this RAB establishment request, the procedure is finally completed with the Session Activation acknowledgement sent to the UE and the UE can initiate transfer of voice and/or data traffic.

![Figure 2.1: UMTS Cellular Network Architecture and Radio Bearer Connections](image-url)
2.2 Handover Procedures

Handovers are needed to maintain sessions when a UE moves between cells. Figure 2.2 shows the movement of a UE in a cellular network of small cells overlaid by the macro cell. Next, we provide a brief description of the relevant features for the handover procedure.

The cell to which the UE is connected is known as serving cell. The UE maintains a list of cells in a list called the Neighboring Cell List. The cells in the Monitored Set continuously transmit the scrambling code matched with their identity through a common pilot channel. The UE measures the signal quality of each cell using this pilot signal. As the UE moves closer to the edge of the serving cell, a handover condition may be met. For example, the handover condition could be the serving cell’s signal quality to be lesser than a set threshold or may be in a comparable range of the signal quality of a neighboring cell. This neighboring cell is known as the target cell. If the Handover condition is stable for a period known as Time-to-Trigger (TTT), the UE sends a measurement report (MR) requesting a radio link to the target cell. The TTT is primarily used to improve the stability of the MR prepared by the UE and reduce the risk of the UE sending MR too early.

The RNC evaluates the request to check if the target cell can satisfy the QoS
requirement of the UE. If approved, the RNC sends a Handover Command (HC) to the UE. The condition of the UE unable to receive any signal from serving cell as it moves farther away is called *outage*. We define the time interval between the time instant when the handover condition is met and the time instant when the UE reaches outage as the *handover region* between the serving cell and the target cell. If the HC reception at the UE falls outside the handover region then the call/session gets dropped. This is known as a *handover failure*. Thus, for a successful handover, it is essential for the UE to receive HC within the Handover region.

In a network with small cells deployment, four types of handovers can occur during a call:

- **Macro-to-macro handover**: Handover from one sector of a macro cell to another sector of the same or different macro cell.

- **Small-to-Small handover**: Handover from one small cell to another small cell.

- **Small-to-macro handover**: Handover from a small cell to a sector of a macro cell.

- **Macro-to-small handover**: Handover from a sector of a macro cell to a small cell.

Figure 2.3 illustrates a handover event for the case of macro cell as the serving cell and small cell as the target cell. There are two HCs shown in the figure. The green HC being received before outage is met results in successful handover. The red HC that would reach the UE after it enters outage leads to handover failure subsequently the call getting dropped.
Figure 2.3: Handover event illustration for the case of macro cell as serving cell and small cell as target cell.
2.3 Mobility Management and Handover Challenges

We now outline the challenges related to mobility management of users and handovers introduced by small cell deployment:

(i) *Abrupt Cell Boundaries*: In traditional macro cell networks, the UE typically uses the same set of handover parameters such as TTT throughout the network. Due to lower transmit power and smaller height than macro cell, a small cell’s path loss curve is steeper and smaller as shown in Figure 2.3. However, the handover parameter setting does not take into account the cell size of the serving cell and target cell during handovers. Thus, the presence of small cells as either the serving cell or target cell reduces the handover region compared to a macro-to-macro handover scenario. According to this hypothesis, the small-to-small handovers have the highest chance of failing followed by small-to-macro handovers and macro-to-small handovers.

(ii) *Velocity*: The length of the handover region also depends on the speed of the UE. The UE speed estimation based on TTT scaling has been already adopted in LTE technology [4]. Inspite of the UE speed based scaling of TTT, the worst case scenario of a handover is that of a high-speed moving UE requesting a handover from one small cell to another small cell.

(iii) *Neighboring Cell List*: With the small cell deployment, there are more number of cells in the range of the UE. To reduce call drops, all potential neighbors must be included in the list. Otherwise, the UE will not measure the signal quality of a target cell that provides good signal quality and may lead to handover failure. Thus, there is an additional overhead involved in exchanging larger neighboring cell lists between the serving cell and the UE and signal measurements reported by the UE to the serving cell [5]. This additional overhead increases the delay in the UE receiving handover command and thus increases the likelihood of handover failure. This challenge is applicable to all types of handover including macro-to-macro handovers due
to exchange of longer neighboring cell list information.

(iv) Range Expansion: The range expansion bias brings forward the trigger timing of the handover entry condition. Consequently, the macro cell users are handed over to the small cell much earlier. However, if the small cells and macro cells operate on the same carrier frequency (for example, 1900 MHz), then the users in the expanded region of small cells suffer from high interference from macro cells. Even with a robust interference management technique, a high range expansion bias can make the signal quality of users in the expanded region worse than the signal quality threshold. This leads to handover failures due to too early trigger timing.
In this section, we present our results from analyzing fine-grained voice service measurements using call detail records collected from an operational cellular network comprising both small as well as macro cells. The call detail records (also referred to here, as CDRs) are collected over 14 days with deployments of the small/macro cell across the whole of United States. We expect that the number of handovers for highly mobile users increases with the increasing number of small cells deployed within a region. We use real-world data to understand the nature and implications of the handovers on the service quality experienced by the users.

In Section 3.2, we present the distribution of total number of handovers and different types of handovers (for example, small-to-small, small-to-macro) observed using the call trajectories. In Section 3.3, we analyze the distribution of the additional handovers introduced by small cell deployment relative to the scenario without small cell deployment. This captures the changes introduced due to small cell deployments in the regions. The calls that previously had a small number of handovers because of larger coverage from a macro cell would potentially have a large number of handovers due to smaller coverage from small cells. We study the relationship between the number of handovers and call duration in Section 3.4. Longer calls for highly mobile
users are expected to have a higher number of handovers. We provide insight into which type of handovers are dominant in a call of small duration versus call of long duration. Finally, in Section 3.5, we analyze the impact of small cell deployments on service performance as experienced by the users.

3.1 Data Sets

Since our objective was to study the deployment implications of small cells, we collected voice CDRs for the calls that involved at-least one small cell over its trajectory. The call can either originate or terminate at a small cell or a macro cell. We exclude calls that involve only macro cells in their trajectories. Each CDR provides detailed information about the voice call: start time of the call, originating and terminating phone numbers, an ordered list of cells that a call traverses (also, referred to as the call trajectory), air-time or the duration of the call spent on each cell, the switch that records the call, cause code for termination of the call, IMEI/IMSI numbers for the calling number. We explicitly hide the originating and terminating phone numbers and obtain anonymized CDRs for our analysis. We select the details as described below.

(i) Start time: The start time of the call is provided in Greenwich Mean Time (GMT). The granularity of the information is a second.

(ii) Call trajectory: It is an ordered list of cells to which the user (or, UE) was connected within the duration of the call. This will comprise at-least one small cell and zero or more macro cells.

(iii) Airtime for each cell: This captures the duration of an answered call at the granularity of a second for each cell in the call trajectory. The duration for the first cell captures the ringing time along with the time spent on that cell.

(ii) Cause code for termination of call: Each CDR is labeled with a cause code
for termination either it is successful call (call termination originated from the user and normally terminated by the network), a blocked call (failed attempt and blocked by the network either due to insufficient radio or core network resources, high interference), or a dropped call (an ongoing call abnormally terminated by the network due to radio network issues such as handovers, uplink or downlink interference, or radio link protocol timer expirations).

We observed an extremely high percentage of calls originating at the small cell as compared to the macro cell. This highlights an interesting behavior from operational deployments of small cells that the user equipment (UE) prefers a small cell due to its better signal strength and coverage.

### 3.2 User Mobility and Handover Analysis

We use the trajectory of the call to calculate the number of handovers within a call, the different types of handovers, their distributions and the unique cells traversed. Our expectation is that the number of handovers will increase with the deployment of small cells.

#### 3.2.1 Total Number of Handovers

The cellular operator has deployed the small cells in a strategic manner. Locations with high traffic demand are identified for the deployment. The network planning team manually evaluate the performance of individual locations. Such field trials are dependent of lca traffic patterns and wireless channel characteristics. A large-scale assessment will allow us to study the mobility pattern of small cell users independent of the local traffic patterns.

Figure 3.1 shows the cumulative distribution of the total number of handovers
occurring in an answered call. Recall that these answered calls involve at-least one small cell and zero or more macro cells. Interestingly, a significant percentage (84.7%) of the answered calls do not involve any handovers and thus, originate and terminate at the same small cell. Thus, a high percentage of calls involving small cells being handled solely by a single small cell throughout the call duration is a positive indicator of the capacity and coverage impact of small cell deployment.

It might be the case that majority of the calls are having a very low call duration leading to this high number of calls with no handovers. If the call duration is low, then the chances of user facing handover are low. To understand further, we also plot the cumulative distribution for the calls belonging to the top 75%-ile of call duration. We observe only a slight decrease in the percentage of calls having no handover. The decrease is expected as the calls considered for this case have higher call duration and thus higher likelihood of moving outside the originating cell. We refer to such users with zero handovers as stationary users. 11.2% of the answered calls comprises a single handover this could either be a small-to-small, small-to-macro, or macro-to-small cell handover.

Next, we aim to dig deeper into the mobility pattern of the users based on the calls during which handovers occurred. We classify the answered calls into the following categories:

(i) Stationary call: An answered call with zero handovers i.e., a single small cell is able to handle the call.

(ii) Mobile call: An answered call during which a minimum of one handover occurs.
3.2.2 Number of Handovers of Different Types and Distribution

We label a handover type using either small-to-small, small-to-macro, macro-to-small, or macro-to-macro and count the number of handovers of these types for each mobile call. Our goal is to understand if certain types of handovers are dominating for the mobile calls. For example, too many small-to-small cell handovers for a highly mobile user is indicative of a trajectory covering multiple small cells. One alternative is to camp such a user onto a macro cell to reduce the risk associated with a handover failure on the small cell.

Figure 3.2 shows the cumulative distribution of the normalized number of handovers of each type occurring in a mobile call across all calls. We make the following observations:

(i) A very small percentage (0.05%) of the calls have small-to-small handovers. This is surprising result shows that when users are moving out of a small cell, their calls are most likely to be handed over to the macro cell. One plausible explanation is
that the target macro cell better qualifies for satisfying the QoS requirements imposed by the users.

(ii) For macro-to-small cell handovers, we observed a very high success percentage. This is because of the resources being made available by the small cell in case of congestion or failures at the macro cells.

(iii) Macro-to-macro handovers have the highest mean of handovers per mobile call compared to other types of handovers.

Figure 3.2: Cumulative Distribution of the normalized number of handovers of different types during a mobile call

We now explore the expected percentage of each handover type in a mobile call. We define the handover type percentage \( P_j(i) \) of handover type \( j \) in a mobile call \( i \) as

\[
P_j(i) = \frac{100 \times \text{No. of handovers of type } j \text{ in } i}{\text{Total no. of handovers in } i}
\]  

(3.1)

For example, if a mobile call originates in a macro cell, gets handed over to a small
cell and terminates at the same small cell, then it will have 0%, 0%, 0% and 100% as handover type percentage for macro-to-macro, small-to-small, small-to-macro and macro-to-small handovers respectively. Figure 3.3 shows the cumulative distribution of the handover type percentage for each handover type across all the mobile calls in our dataset. We make the following observations:

(i) The small-to-macro handover type percentage reaches 100% at a value of 0.28 on the y-axis. This means 72% of the mobile calls have only small-to-macro handover. Thus, 72% of the mobile calls originate at the small cell, get handed over to a macro cell and terminate in the macro cell. This result concurs with our earlier explanation that the call of a mobile user moving out of small cell has more likelihood of handing over to macro cell.

(ii) Analogous to our previous section finding, in which we observed a very low number of small-to-small handovers occurring during a mobile call, the small-to-small handover type percentage stays close to zero for almost all the mobile calls.

Figure 3.3: Cumulative distribution of the handover percentage type for mobile calls
3.2.3 Unique Cells Traversed

Figure 3.4 shows the cumulative distribution of the number of unique small cells and unique macro cell sectors traversed during a mobile call. 99.54% of the mobile calls have only one small cell involved during the call. The remaining 0.46% of the mobile calls have two small cells involved during the call. This is very different from expectation that small cell deployment leads to increase in handovers across small cells as the user moves in and moves out of the small cells. This is possible either because a small number of small cells have been deployed within a particular region, or the handover protocols have been designed and implemented in a fashion to minimize small-to-small cell handovers by camping the highly mobile users onto the small cell.

Figure 3.4: Cumulative Distribution of the number of unique cells traversed during a mobile call
3.3 Additional Handovers

In this section, we analyze the additional handovers introduced by small cells during a mobile call. For this purpose, firstly, we calculate the number of handovers that would have taken place in a hypothetical macro only network. For example, a mobile call starting in a small cell, moving to a macro cell and ending there would have had zero handovers in macro only network. In this example, there is one additional handover due to small cell deployment. Another example, a mobile call with the following trajectory macro A → small B → macro A would have had zero handovers in macro only network. In this example, there are two additional handovers.

We employ the metric extra handovers % for our purpose. The extra handovers % $E(i)$ of mobile call $i$ is defined as

$$E(i) = 100 \times \frac{Y(i) - X(i)}{X(i)}$$

(3.2)

where

$X(i) = \text{No. of handovers in macro only network for } i$ and $Y(i) = \text{No. of handovers with small cells}$

We are interested in the relative increase in handovers apart from the absolute increase in handovers due to small cells. Table 3.1 shows two particular cases of a mobile call. In both cases, the extra number of handovers due to small cells is the same. The number of handovers in macro only network is indicative of the distance covered during a call. This is because of the much bigger coverage area of macro cell. We observe that the second case represents a much worse scenario because user has faced same number of additional handovers due to small cells for a much smaller distance covered compared to the first case.

Simulation studies [15] have shown that the relative increase in handovers for a
naive small cell deployment is 120% - 140%. However, none of the existing works have analyzed the variation of extra handovers % with the number of handovers in macro only network. In a real network, the user mobility is not controllable and the density of small cells varies for each covering macro cell. It is important to learn the distribution of the extra handovers % among the mobile calls to understand the impact of small cell deployment on handovers.

<table>
<thead>
<tr>
<th>Macro Only Handovers</th>
<th>Extra Handovers</th>
<th>Extra Handovers %</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>30</td>
<td>100%</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>600%</td>
</tr>
</tbody>
</table>

Table 3.1: Absolute and Relative Increase in handovers due to small cells

If there are no handovers in a macro only network for mobile call $i$, $E(i)$ would be positive infinity. We find that 74.5% of the mobile calls belonged to this category. Interestingly, all of these calls had just one extra handover introduced by small cell deployment. Thus, calls with no handovers in a macro only network have just one extra handover in a network with small cell deployment.

Next, we would like to analyze calls that are having one or more handovers in macro only network. Figure 3.5 shows the histogram of extra handovers percentage for calls with one or more handovers in macro only network. We make the following observations:

(i) We observe there are four major peaks formed. The peaks are at 10%, 50%, 100% and 200%. The peak at 10% has the highest mean although only by a small margin to the peaks at 50% and 100%. The peak at 200% is the smallest indicating the low percentage of the calls with such a high overhead due to small cell deployment.

(ii) The calls belonging to the 10%-peak curve are having the number of macro-macro handovers much greater than the sum of small to macro handovers and macro to small handovers. These are calls of highly mobile users covering a lot of distance.

The calls with extra handovers percentage of 100% and more are of the highest
concern and understanding their relationship with the user mobility is needed. For example, a call with 100% extra handovers percentage and having 10 handovers in macro only network represents a more drastic situation than a call with 100% extra handovers percentage and having just 1 handover in macro only network.

Figure 3.5: Histogram of the extra handovers percentage for calls with one or more handovers in macro only network.

Figure 3.6 shows the extra handovers percentage as a variation of the number of handovers in macro only network. The plot also has errorbars with the top bar representing the maximum value and bottom bar representing the minimum value of extra handovers % observed in the dataset for a particular number of handovers in macro only network. We make the following observations:

(i) The graph can be divided into three categories based on the number of handovers in macro only network. The number of handovers in macro only network are indicative of the distance covered during the call as the coverage area of the macro cell is in the order of kilometres. Firstly, low mobility represents one to three handovers. The extra handovers percentage goes up to 200% for this category. Secondly,
high mobility represents the number of handovers from 4 to 18 handovers. The extra handovers percentage goes up to 80% for this category. Lastly, the very high mobility represents the number of handovers greater than 18. The extra handovers percentage goes only up to 40% for this category.

(ii) The extra handovers percentage is 200% only for the case of one handover in macro only network. We observe that the mean is around 110 %. This is because of the low number of calls with extra handovers % of 200%.

(iii) The low extra handovers percentage for very high mobility category shows the positive impact of the strategic deployment.

Figure 3.6: Mean extra handovers percentage as a variation of number of handovers in macro only network
3.4 Relationship between Handovers and Call Duration

We analyze the call duration (sometimes, also called as the airtime) for the answered calls. Figure 3.7 shows the comparison of the stationary calls (zero handovers) and mobile calls (more than zero handovers) for the percentile values of the airtime. *The airtime percentile values for the mobile calls are typically higher than that of stationary calls and the difference increases with increase in percentile value.*

![Figure 3.7: Comparison of stationary calls and mobile calls for percentile values of airtime calls](image)

We expect the longer the airtime of a mobile call, higher is the number of handovers occurred especially in a dense small cell deployment scenario. We would like to observe the variation in the number of handovers for a mobile call with the airtime. For this purpose, we divide the airtime range into intervals of 60 seconds. Each mobile call is placed in the appropriate airtime interval for analysis. The value of 60 seconds is chosen taking into consideration the distribution of airtime for mobile calls we observed in the operational data.
Figure 3.8 shows the variation of the mean number of handovers for each type with the airtime. The x-axis represents the index of the airtime interval. For example, index 2 refers to the set of mobile calls with airtime in the range of $(60, 120]$ seconds. We focus our analysis on the lower 15 airtime intervals as they cover more than 95% of the mobile calls. This can be observed from Figure 3.7. For higher airtime indices, we observed a lower number of mobile calls - this introduces higher variability into the results and hence we eliminate them from our analysis. We present the following observations:

(i) For the lower airtime index of 1 and 2 which constitutes more than 50% of the mobile calls, the mean number of small-to-macro handovers is 1 and higher than rest of the means. A mobile call with low airtime is most likely to have a handover from small to macro cell. This result complements the observations made in Section ?? that over 70% of the mobile calls have only small-to-macro handover as the only type of handover during the call.

(ii) As airtime index increases, the mean number of small-to-macro handover stays close to 1 indicating that the small-to-macro handover still occurs for higher airtime. We observe that the mean number of macro-to-macro handovers consistently increases with the airtime. One explanation is that the mobility pattern of the user is such that once the mobile call is handed over from small to macro cell at some point of the call, it remains outside the coverage area of small cells for the remaining duration of the call. That duration in which it stays can be much longer than that time it stayed in small cells. This is evident from the number of macro-to-macro cell handovers that take place during the call.

(iii) The mean number of macro-to-small handover at index 1 is 0.1276. This implies the presence of macro-to-small cell handovers even in mobile calls with a low airtime. The mean increases slightly as the airtime index increases, but stays below
1 even at high airtime index.

Figure 3.8: Variation of the mean number of handovers with airtime

3.5 Impact on Service Performance

In this section, we study the impact of small cells deployment on service performance experienced by the users. We employ the widely used metric call drop probability as a measure of service performance. To analyze call drop probability in different scenarios, we classify the successfully answered calls based on three criteria:

(i) Mobility: We use the number of handovers to identify if the call is stationary or mobile. The likelihood of a radio interface problem being a handover failure is higher for a mobile call drop in comparison to a stationary call drop since we have the evidence that the user has been moving in the case of a mobile call.

(ii) Terminating Cell: If the call was dropped in a macro cell due to a handover failure, we cannot say for sure if a small cell is involved as the target cell. However, if a call was dropped in small cell due to handover failure, we know for sure smaller coverage of small cell played a part in the call getting dropped.
(iii) **Final cell time:** Lastly, we also incorporate the *final cell time* as the time spent in the final cell (or, terminating cell) of the call trajectory. For stationary calls, the final cell is the same cell in which the call was originated. For mobile calls, the final cell captures a different cell than its previous. Failed calls with only a single cell could either be because of any radio issues in the same cell, or handover failure with it’s neighbor. The expected time of the next handover attempt of a mobile call is higher after it is handed over to macro cell, as compared to a small cell assuming other conditions such as the current call duration, mobility pattern of the user, and expected time of call termination remains same. This is primarily because of the vast difference in coverage area of small cell and macro cell.

### 3.5.1 Final Cell Time

To obtain the interval size of final cell time, we study the distribution of final cell time for different types of calls. Figure 3.9 shows the percentile variation of the final cell time for the different mobility classes. We make the following observations:

(i) The lower percentiles are similar in all of the mobility classes indicating global presence of calls that spent very less time in the final cell before terminating.

(ii) The *small-stationary class remains the highest percentile values from 30%-ile onwards.* This is expected as the entire call duration is taking place in the same cell. Also, the final cell time is higher because there is a lower chance of call getting dropped while being stationary.

(iii) The percentile value of macro-mobile class remains higher than small-mobile class from 20%-ile onwards. As we discussed in Section ??, there is a higher chance of handover failure for handovers outgoing from small cell compared to that of macro cell. Combining both these hypotheses, the probability of call getting dropped due to handover failure is lower when the call is in a macro cell as compared to a small
cell. Thus, the final cell time for a mobile call terminating in a macro cell is higher than that of a mobile call terminating in a small cell.

![Cumulative distribution of Final Cell Time for the different mobility classes](image)

**Figure 3.9:** Cumulative distribution of Final Cell Time for the different mobility classes

### 3.5.2 Dropped Call Analysis

We obtain *Call Drop Probability* $P_{dr}(i, j, k)$ as follows:

Let $X(i, j, k)$ denote the set of answered calls belonging to mobility class $i$, terminating cell class $j$ and final cell time class $k$. Let $X_{dr}(i, j, k)$ denote the set of calls in $X$ that are dropped due to radio interface problems. We choose the value of the final cell interval to be 15 seconds for dropped calls analysis based on observations in Section 2.

$$P_{dr}(i, j, k) = \frac{\text{No. of calls in } X_{dr}(i, j, k)}{\text{No. of calls in } X(i, j, k)} \quad (3.3)$$
Figure 3.10 compares the normalized call drop probability of the mobility classes as a function of final cell time. We make the following observations:

(i) We observe that the call drop probability is the highest for a mobile call terminating in small cell independent of the final cell time. The call drop probability for mobile calls terminating in small cell is higher than the call drop probability of stationary calls terminating in small cells because there is a higher chance the mobile calls were dropped due to handover failures. This result validates the impact of handover failures on the small cells network performance. An important point to note is that the number of calls terminating in small cells is much smaller than the number of calls terminating in macro cells, as discussed in Section ??.

(ii) The call drop probability for a mobile call terminating in a small cell is non-monotonic. Initially, it decreases from the first to third index. This is mainly because a high percentage (around 40%) of the mobile calls terminating in small cells have a final cell time lesser than or equal to 15 seconds. These are the calls that spent enough time in their previous cells and hence remain active for a low time in the terminating cell. Then, it increases as the likelihood of handover attempt increases. However, call drop probability increases only until a certain point after which it decreases. This is because the likelihood of a call termination by the user overtakes the likelihood of handover attempt. We do not observe such strong monotonic changes in the call drop probability of the other two mobility classes. In macro-mobile class, this could be attributed to the bigger cell size. In small-stationary class, the low likelihood of handover attempt is the main reason.

(iii) The call drop probability for a mobile call terminating in a macro cell is the lowest independent of the final cell time. For a handover failure in macro cell, the target cell could be a small cell or a macro cell. We cannot say for sure that the handover failure occurred due to challenge of abrupt cell boundary of small cell.
Whereas for a handover failure in a small cell, we know for sure that there is an abrupt cell boundary as the serving cell is a small cell. Thus, the call drop probability for a call terminating in small cell is higher in comparison to that of a call terminating in macro cell.

Figure 3.10: Comparison of normalized Call Drop Probability as a function of Final Cell Time for different classes of mobility
In this chapter, we analyze the impact of small cell deployment on the data service performance experienced by the users. We resort to coarse-grained measurements here as opposed to fine-grained CDR measurements because data CDRs only comprise the originating cell instead of the whole call trajectory. Coarse-grained measurements are collected by the network equipments and summarized across all calls within the time-granularity of an hour. Our expectation is the traffic offloading and the handover impacts for data sessions should bear similar results as voice service. Here, we focus on a tourist location as opposed to the whole of US. The tourist location has a relatively higher traffic demand and user mobility as opposed to others and thus has a relatively higher number of small cells deployed by the service provider.

We used the latitude-longitude information to identify the small cells in close geographical proximity of the macro cells (within a radius of 1 kilometer). A total of 53 small cells and 5 macro cells were selected for our study. In Section 4.1, we describe the data sets used for our analysis. Section 4.2 describes the mathematical techniques utilized for analyzing the data. In Section 4.3, we study the distribution of the traffic offloaded to the small cells and the correlation between the macro cell traffic and small cell traffic. Finally, in Section 4.4, we analyze the impact of network
events that induce service quality impacts in small cells.

4.1 Data Set

We collected hourly raw cell-level service quality measurements for a period of three months. The measurements were collected for both small cells and macro cells in the selected region. We now describe the relevant key performance indicators computed using the service quality measurements.

(i) Session Attempts: The total number of RRC (Radio Resource Control) connection attempts triggered by the users in a time bin.

(ii) Sessions Activated: The total number of RAB (Radio Access Bearer) Successes in a time bin. A RAB is allocated once end-to-end resources are allocated for the call.

(iii) Accessibility: The percentage of RAB Successes to RRC connection attempts in a time bin. Accessibility is a measure of the successful session attempts triggered by the users in the cellular network.

(iv) Retainability: The percentage of RAB drops to the RAB successes including the successful incoming macro cell to small cell handovers and excluding the outgoing small cell to macro cell handovers in a time bin. Dropped call percentage is inversely related to retainability and can be computed by subtracting retainability from 100.

(v) Small-to-Small Handover Failure Percentage (S-S HOFP): The percentage of the unsuccessful small-small handover attempts made in a time bin.

4.2 Methodology

In this section, we describe the approach for our experiments, including event series formation, processing performed on the real-world data to make our analysis more
robust, and the new statistical correlation framework designed to find the aggregate correlation score across multiple small cells.

### 4.2.1 Event Series Formation

We construct a time-series for each key performance indicator by dividing the original series into \( n \) equal time-bins. This step is performed for the key performance indicator of each small cell and macro cell. For example, for a metric like session attempts, we use each hourly time-bin to capture the total number of PS RRC Connection Attempts.

### 4.2.2 Data Sanitization

As shown in Figure 4.1, the event series possess characteristics such as time of day, weekday versus weekend. To make a proper assessment, there is a need to sanitize the event series from such diverse characteristics. We employ a robust singular value decomposition-based approach [8] that performs local subspace computation using \( l_1 \)-norm. It decomposes a time-series into normal and residual subspace. Anomalies are extracting by statistical thresholding on the residual subspace. This method performs iterative optimization by using augmented Lagrangian multipliers at each iteration thereby implicitly accounting for any seasonality, stationarity, or high variability in the event-series and is more robust to outlier effects compared to \( l_2 \) norm.

### 4.2.3 Statistical Correlation

Given a symptom event and a region of \( M \) small cells, the goal is to find the statistical dependency of the symptom event and potential root cause event series across the \( M \) cells. Figure 4.2 shows the methodology flow diagram for the analysis performed in this section. For example, we employ statistical correlation to quantify the impact of
potential causes that lead to a data session being terminated from the network side. Simple co-occurrence based approaches are ineffective due to high false positives as co-occurrences may be a mere coincidence or one-time event. Next, we briefly describe our approach.

Let $P_1, P_2, ..., P_M$ represent the residual symptom event series of the $M$ cells respectively. Let $Q_1, Q_2, ..., Q_M$ represent the residual root cause event series of the $M$ cells respectively. Each of the series contains $N$ samples. Firstly, we carry out the spatial aggregation into $P$ and $Q$ as follows:

$$P = \frac{\sum_{i=1}^{M} P_i}{M}$$  \hspace{1cm} (4.1)
\[ Q = \frac{\sum_{i=1}^{M} Q_i}{M} \]  

(4.2)

We need to exclude the cross-interaction between \( P_i \) and \( Q_j \) where \( i \) and \( j \) are not equal. Thus, we calculate modified form of Pearson’s correlation coefficient and the population correlation coefficient \( C_{P,Q}^{agg} \) between \( P \) and \( Q \) is given by

\[
C_{P,Q}^{agg} = \frac{Cov(P, Q)}{\sqrt{Var(P)Var(Q)}}
\]  

(4.3)

where

\[
Cov(P, Q) = \sum_{i=1}^{M} \frac{Covariance(P_i, Q_i)}{M}
\]  

(4.4)

and

\[
Var(X) = \frac{\sum_{i=1}^{M} Variance(X_i)}{M}
\]  

(4.5)

Next, we test the statistical significance of the correlation. If the population coefficient is non-zero then the correlation coefficient cannot be assumed to have a standard normal distribution. A solution to this problem is the Fisher transformation which exhibits an almost normal distribution. Fisher’s transform is applied to test the hypothesis,
$$z_{agg} = \frac{1}{2} \ln \left[ \frac{1 + C_{P,Q}^{agg}}{1 - C_{P,Q}^{agg}} \right]$$ \hspace{1cm} (4.6)$$

The standard error is given by

$$\frac{1}{\sqrt{N - 3}}$$ \hspace{1cm} (4.7)$$

To test the statistical significance, the samples need to be independent. Although devoid of factors such as seasonality, the residual time-series still exhibit autocorrelation as they are collected from real physical systems. The autocorrelation is eliminated by incorporating a non-zero first order autocorrelation coefficient and thus obtaining a reduced sample size known as effective sample size. The first order autocorrelations $r_1(P)$ and $r_1(Q)$ are obtained for the aggregate residual series $P$ and $Q$ as follows

$$r_1(P) = \frac{Cov(P, P + 1)}{Var(P)}$$ \hspace{1cm} (4.8)$$

and

$$r_1(Q) = \frac{Cov(Q, Q + 1)}{Var(Q)}$$ \hspace{1cm} (4.9)$$

where $P + 1$ and $Q + 1$ are one time bin shifted versions of $P$ and $Q$ respectively. The effective sample size $N_{eff}$ is defined as
\[ N_{eff} = m N \frac{1 - r_1(P) r_1(Q)}{1 + r_1(P) r_1(Q)} \]  

(4.10)

Assuming the Fisher transformation is asymptotically Gaussian for large effective sample size, the correlation score is defined as

\[ score = z_{agg} \sqrt{N_{eff} - 3}, \]  

(4.11)

We consider the correlation score is considered significant if it falls outside of the \([-2.33, 2.33]\) range. With the Fisher transformation sample distribution asymptotically Gaussian, this yields a low false positive ratio of 1%. Similar mechanism can be applied to calculate the correlation score at each individual small cell.

For our experiments, our framework outputs the aggregate correlation score of all small cells and individual correlation score for each tuple of small cell between the symptom event and potential root cause event. We classify a aggregate correlation between the symptom event series and another event series as significant if it falls outside \([-2.33, 2.33]\), as discussed earlier.

Figure 4.2: Methodology
4.3 Macro Cell - Small Cell Interactions

We employ the percentage of total traffic offloaded to small cells as a measure of the benefits provided by small cell deployment. If there were no small cells, a significant percentage of session attempts at small cells would instead occur at the overlaid macro cells, thus increasing the likelihood of traffic congestion at macro cells. By offloading the traffic from the macro cells, small cells reduce the likelihood of traffic congestion in the macro cells. The higher the traffic offload, the higher the usage of capacity gains provided by small cells. Although, a very high traffic offload may cause traffic congestion at the small cells. We had discussed earlier in Section ?? that small cells may be provided with cell selection bias to increase the traffic offload. For our analysis, we assume the service provider has chosen the value of cell selection bias for each small cell that performs optimal load balancing between small cells and macro cells based on current network conditions.

We define traffic load $L_c(t)$ by the total number of session attempts made at cell $c$ in hour $t$. We define the traffic offload percentage $O(t)$ in hour $t$ as

$$O(t) = 100 \times \frac{\sum_{s \in S} L_s(t)}{\sum_{s \in S} L_s(t) + \sum_{m \in M} L_m(t)} \quad (4.12)$$

where $S$ is the set of small cells and $M$ is the set of macro cells in the selected region.

In Figure 4.3, the median value of traffic offload percentage is 10.5%. Traffic offload percentage has the highest value of 50.4% which is a high fraction of total traffic load. This provides us confidence in the benefits of deploying small cells. However, a high traffic offload percentage may not necessarily correspond to a case of high traffic load in the network. The macro cell traffic might be low in that hour.
causing the traffic offload percentage to increase.

To gain a better understanding, we study the correlation between the macro cell traffic and small cell traffic. For this purpose, we form the residual series for the traffic load series using techniques discussed in Section ?? and perform a correlation test. We find the macro cell traffic and small cell traffic to be strongly correlated with a correlation score of 3.39. Figure 4.4 shows the scatter plot for the macro cell traffic and small cell traffic. The least squares regression line has a positive slope validating the positive correlation between the macro cell traffic and small cell traffic. The traffic offload to small cells is increased when the traffic load is high in macro cells. This indicates the benefit of small cell deployment of relieving macro cells from a significant fraction of the traffic under high load conditions. There might be cases where traffic offload to the small cells is so high that it starts affecting the service performance of the small cells. We defer the study of the impact of traffic load on retainability to Section ??.
4.4 Data Retainability

Service performance (data retainability) could be impacted due to several network events such as traffic load (congestion), handover failures, existence of coverage holes, or cells being unavailable due to power outage or maintenance events. For our experiments, we use *Session Attempts* in a time-bin at a small cell as a measure of the Traffic Load in that small cell. Small Cell Unavailability refers to a power outage or maintenance event at a small cell due to which the users connected to that small cells face abrupt session termination. Similar termination can also occur due to a re-start at the small cell.

The statistical correlation test described in Section ?? is applied by taking retainability as the symptom event series. We conducted the test for hourly measurements collected for a long period of three months to add statistical confidence to our result.

Table 4.1 shows the result of the statistical correlation test. The correlation score in the middle column is the aggregate value for all of the 53 small cells in the selected region.
region. We also have an individual correlation score between the symptom and other event series for each cell. The percentage of cells in which there is a significant correlation score for a network event is used to indicate the impact on the symptom among the small cells. To recap, a correlation score less than -2.33 denotes a significant negative correlation score between the two event series.

<table>
<thead>
<tr>
<th>Event Series</th>
<th>Correlation Score</th>
<th>Percentage Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Load</td>
<td>-9.1</td>
<td>54.7</td>
</tr>
<tr>
<td>S-S Handover Failure Percentage</td>
<td>-92.0</td>
<td>84.9</td>
</tr>
<tr>
<td>Cell Unavailability</td>
<td>-14.8</td>
<td>26.4</td>
</tr>
<tr>
<td>Cell Re-start</td>
<td>-3.6</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Table 4.1: Correlation Score Table with Symptom Event: Retainability

All the four network events have a significant negative correlation validating their impact on the retainability. The S-S Handover Failure percentage has the highest correlation score. *More than 84% of the small cells in the region have a significant negative correlation score between retainability and small-to-small handover failure percentage indicating widespread impact.* These results show that handover failures are one of the dominating contributors to data service quality issues in operational networks as compared to other events. Small cell to small cell handover failures involves the worst scenario of the challenge of abrupt cell boundaries. This is because the serving cell is a small cell and the target cell is also a small cell. Moreover, as the tourist location has a relatively higher density of small cells, there is also the challenge of increased neighboring cell list. Both these challenges contribute to occurrence of small cell to small cell handover failures in the location thereby impacting data service quality. These challenges were discussed in Section ??.

We observe that Cell Unavailability has a higher correlation score than the traffic load in the absolute sense. However, the percentage spread of Cell Unavailability is less than 50% of the percentage spread of traffic load. This indicates that there are a few small cells that are frequently unavailable due to power outage, lead to an impact
on retainability.

Figure 4.5 provides a visual snapshot of the relationship between retainability event series and S-S HOFP event series for a small cell. We observe that many of the dips in retainability are matched by spikes in S-S HOFP. However, there are a few dips in retainability with no matching spike in S-S HOFP. Such dips are due to other network events.

Figure 4.5: A snapshot of retainability and small-small handover failure percentage for one of the small cells. The y-axis is absent for proprietary reasons.

The above results are the operational case studies performed on our statistical correlation framework. These results are confirmed by the cellular operators demonstrating the effectiveness of our approach.
Chapter 5

Related Work

To the best of our knowledge, this paper presents the first detailed measurement study of voice and data service performance of an operational small-cell cellular network. We summarize related studies as follows.

Macro-Cell Performance Studies: Recent cellular measurement studies have characterised user mobility and behaviour. In [9], the authors found a large fraction of the users have negligible mobility and significant portion of traffic is generated by the more mobile users. Mobility performance testing in several end-user mobile scenarios such as trains, subways etc. has been conducted in [10, 11]. In [10], the authors find that mobility improves fairness in bandwidth allocation among users and traffic flows although degrading throughput. Mobility patterns have also been studied specific to traffic [12] and crowded events [7]. Call durations have been studied in [13, 14]. In contrast to these works, we focus on the service performance implications of the changes introduced by the small cell deployment.

Small Cells Handover Simulation and Modeling Studies: Few system-level simulations have been conducted to study the impact of small cell deployments on the mobility performance in LTE-Advanced systems. The results in [15, 16] show that the handover failure rate and number of mobility events monotonically increase
with user speed and density of small cells deployed. In [15], the handover failure rate is shown to be highest for a high speed user connected to a cellular network of small cells and macro cells operating on the same carrier frequency. In [16], the authors find the main reason for handover failure is the handover request being made too late due to the unstable signal strengths of the small cells. In [3], the authors analyse the handover performance under varying conditions of small cell range expansion and interference management. In [17], the authors study user association schemes for optimal traffic offload to small cells. In contrast to these works, we use a global view of the cellular network with small cell deployment to analyse service performance. All of these works employ a naive small cell deployment setting. Unlike related works which show a 120%-140% increase in handovers due to small cells, we observe that, in an operational network, the extra handovers % is below 10% for the very high mobile users.

**Statistical Correlation.** In NICE [18], the authors built a statistical correlation framework for the network event time series of large IPTV networks. The correlation technique was applied on simplistic binary time series whose correlations are easier to interpret in comparison to our non-binary residual time series. Also, this framework did not involve spatial aggregation of network events and focused on events at the same data source. In contrast, our framework calculates the aggregate correlation score for a given spatial footprint.
In this thesis, we conducted a detailed measurement study of voice and data service offered by a large-scale operational small cell network. Using call detail records for voice service, we observed that (i) the majority of the calls involving small cells originate and terminate at the same small cell, (iii) the calls with high number of handovers between macro cells have negligible overhead of handovers involving small cells and (iii) the call drop probability for a mobile call terminating at a small cell is higher as compared to stationary call or mobile call terminating at a macro cell. Further, we proposed a new service quality framework for estimating the aggregate statistical dependency between two events across multiple small cells. The tests on the framework are confirmed by the cellular operators demonstrating its effectiveness. The framework is not dependent on small cells and can be extended to other technologies and data sets. Using data performance measurements collected, we observed that (i) the small cells take up more traffic during conditions of high traffic load in the cellular network, thus alleviating the impact of traffic congestion in the macro cells, (ii) small-to-small cell handover failures are one of the dominating causes for service quality impacts captured using data retainability. Our findings can be used to design a set of handover policies for improvement of service performance and modeling of
call drop probability in operational small cells deployment overlaid by macro cells.
References


