A low-latency control plane for dense cellular networks

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Abstract
In order to keep up with the increasing demands for capacity, cellular networks are becoming increasingly dense and heterogeneous. Dense deployments are expected to provide a linear capacity scaling with the number of small cells deployed due to spatial reuse gains. However in practice network capacity is severely limited in dense networks due to interference. The primary reason is that the current LTE control plane deployment model has very high latency and is unable to cope with the demand of implementing interference management techniques that require coordination on a millisecond timeframe.

This paper presents SwiftC, a novel low-latency control plane design for LTE networks. SwiftC’s novel contribution is a design for efficiently sending and receiving control plane messages over the LTE spectrum itself, thus creating a direct and low-latency coordination signaling link between small cells and the macro cell. SwiftC builds on recent work in full duplex radios and shows via prototype implementations that a low latency control plane can be built over the existing LTE network without wasting licensed spectrum. We also show the benefits of SwiftC in implementing complex interference management techniques, and show that with SwiftC small cell deployments can achieve almost a linear capacity scaling with every small cell deployed.

1. INTRODUCTION
Dense cellular networks with several small cells deployed per macrocell are expected to provide significant gains, increasing capacity almost linearly with every deployed small cell. The benefits come from two factors: clients are closer to the base station (BS) leading to higher SNR links, and the load per BS is significantly lower due to the smaller coverage area leading to higher per user throughput and higher spatial reuse. Consequently, there is tremendous interest from industry to move towards such architectures [1], [2] and preliminary deployments have already begun.

A big challenge however is the lack of licensed spectrum. Ideally, operators would like to operate adjacent small cells on different frequencies so as to avoid interference and get the capacity scaling benefits. Unfortunately, licensed spectrum is scarce and expensive. For example, Verizon and AT&T own only 20MHz of contiguous downlink spectrum each licensed for LTE in the 700MHz band, which is too small to divide into multiple channels efficiently (dividing requires guard bands which can be quite wasteful given the limited spectrum widths). Consequently, adjacent small cells are expected to operate on the same channel. In industry parlance, this is referred to as network deployments with a spectrum reuse factor of one, which is how current LTE networks are being deployed.

The problem therefore is that small cells are going to cause significant interference to each other as well as to the macro BS whose larger coverage area spans the small cell coverage areas. Further, since licensed spectrum is typically in the lower carrier frequencies (700-900MHz or 1.8GHz), radio signals propagate farther, and thus interference is exacerbated. Left unmanaged, interference will severely limit network capacity and prevent small cells from achieving the expected linear capacity scaling.

To cope, the cellular standards body 3GPP has introduced several control plane mechanisms to manage interference. The default mode is to just ignore the interference (i.e., treat it as noise) and this is in fact the most widely used mechanism today, but as we will show in Section 3, in this case network capacity is severely limited by interference. Recently, a newer set of mechanisms known as eICIC (enhanced Inter Cell Interference Coordination) has been introduced which essentially tries to schedule transmissions from the macro BS and the small cells in different time-frequency slots so that they avoid interfering with each other. A final more sophisticated mechanism is CoMP (Coordinated Multi Point), which attempts to exploit interference by jointly coding the transmission across multiple small cell BSes such that these BSes mimic a large MIMO antenna array. This mechanism requires the exchange of channel state information between the BSes, coordination on a joint pre-coding vector at all the BSes and synchronized transmission. This mechanism can provide large benefits, and unlike the other two mechanisms, can in fact turn interference into an advantage rather than a liability.

Our problem thesis in this paper is that the current control plane and deployment architecture for the radio access network (RAN) in cellular networks is not capable of realizing the interference coordination mechanisms described above.
The key challenge is latency. The LTE control plane is based on the X2 interface [7] which is a logical interface defined over the physical backhaul links used to connect the BSes back to the packet core of the operator. The physical backhaul links use a variety of technologies, mostly out of necessity. Given the density of small cell deployments, and the fact that they have to be deployed in urban areas, operators are forced to use whatever backhaul connectivity is available (ranging from cable networks to DSL to public fiber if its available). All of these physical network options exhibit latencies of 10-15ms to the cellular packet core in the best case, and often much higher.

Such high latencies pose problems in managing interference. Specifically, our analysis in Section 3 shows that with such latencies, network performance can often be worse with interference management mechanisms such as CoMP than without! The reason is that these mechanisms depend upon neighboring BSes coordinating with each other by exchanging channel state information and making joint scheduling and coding decisions. However such coordination has to occur at the same granularity as channel coherence times, which is around $4 - 5\,\text{ms}$ ($90\%$ coherence) even for static and walking mobility users in urban environments. Hence a coordination latency of $10\,\text{ms}$ would mean that the channel state information that was shared is only about $80\%$ correlated with the actual channel during transmission (or in other words, has a $staleness$ of $20\%$, as we define later). Staleness shows up as increased interference and decrease in SINR, reducing network capacity. The effect is worsened in dense networks because the increase in interference from staleness is proportional to the channel strength, which is by definition high in dense networks.

To tackle this problem, in this paper we present the design and implementation of a novel low-latency and efficient control plane, SwiftC, for cellular networks. SwiftC’s key architectural insight is to physically decouple the control and data plane backhaul connectivity and use different connectivity options for them. We argue that imposing the requirement that a single backhaul technology satisfy the stringent latency requirement that the LTE control plane requires and also the high bandwidth requirement that the data plane desires leads to unnecessarily expensive and complex backhaul designs, which in turn makes small cells expensive or infeasible to deploy. We argue that its in fact better to design the backhaul for the control plane separately to satisfy the low latency requirement.

SwiftC’s physical control plane design is built on the LTE air interface itself as the physical technology, in other words we use the macro LTE network itself as the control plane backhaul network for the small cell. Consequently SwiftC inherits the latency guarantees that LTE itself provides, namely $1\,\text{ms}$ best case latency if needed for urgent transmissions (the size of the LTE subframe). The natural concern with this approach of course is whether we are using up scarce LTE spectrum to build a control plane. In this paper we present a novel design for the small cells that allows us to build this control plane almost for free by leveraging recent work on full duplex radios. Specifically, we enable each small cell to connect to the macro base station as if it is a phone, on the same frequencies it is using for serving clients connected to itself. The idea is that when the small cell is receiving transmissions from the phones connected to it on the uplink frequency, it can turn around and transmit control frames to the macro base station at the same time on the same frequency because of full duplex capability. The idea works analogously in the downlink direction, at the same time as the small cell is receiving control messages from the macro BS on the downlink frequency, it can transmit to the phones connected to it. Hence no capacity is lost at the small cell, and the control is piggybacked on the same frequencies. Meanwhile the data plane backhaul can be provided using whatever connectivity is available as long as it has sufficient bandwidth, it does not have to also satisfy the low latency requirement at the same time.

We design and implement SwiftC and show the benefits of such a low latency control plane in managing interference in dense cellular networks. We show that with SwiftC, overall network capacity can scale almost linearly with the number of small cells deployed.

Finally, we note that recently some operators such as China Mobile have proposed C-RAN [4], an architecture where the entire baseband of multiple base stations is centralized and processed in a datacenter. The idea is that each base station would only be a simple radio, and they would send/receive IQ digital samples itself from the centralized datacenter. So all the signal processing and protocol handling is done completely in the centralized location, and consequently C-RAN can definitely implement all of the above interference control mechanisms easily. However C-RAN is extremely expensive and in many scenarios impossible to deploy. This is because C-RAN requires that every base station be connected by direct fiber links with less than 5ms latency with several gigabits of bandwidth. Such a fiber deployment is extremely expensive, and in many cases infeasible in Europe and the US because cities have already been built out. SwiftC is also architecturally simpler. Operators now have the flexibility to chose whatever backhaul is available for data backhaul without having to worry about whether that option can satisfy the stringent requirements for the RAN control plane. We believe this can greatly simplify small cell deployment.

2. BACKGROUND

2.1 LTE Small Cells and the Control Plane

The 3GPP LTE standards define two base station types (also called evolved NodeBs or eNBs) that are meant for small cell deployments [6] - medium range eNBs (metro or micro cells) and local area eNBs (pico cells), see Table 1. Future urban outdoor networks are expected to be increasingly heterogeneous with these small cells deployed within exist-
ing macro cell coverage areas to increase network capacity and extend service coverage. Typical deployment models suggest deploying around 4-12 small cells per macro sector, or 12-36 small cells per macro eNB assuming a 3-sector macro eNB. With increasing density, there is going to be an increasing need for coordination between groups of small cells as well as between small cells and macrocells in order to use the radio resources more efficiently.

Table 1: Typical urban small cell properties

|                        | Microcell | Picocell |
|------------------------|-----------|----------|
| Max Tx power           | +38dBm    | +24dBm   |
| Location               | 200-500m  | 50-100m  |
| Indoor                 | Outdoor   | Indoor/Outdoor |
| Simul. Active Users    | 32-64     | 32-64    |

The 3GPP LTE standards specify a control plane for LTE to implement interference coordination and other network management functions. The control plane is built on an X2 interface that interconnects neighboring base stations [7]. X2 is a logical point-to-point interface that can be switched over the existing IP transport network that is serving as the backhaul for the base station to the operator’s packet core network. The typical organization of the control plane has the macro eNB acting as the logically centralized point with network and user state information being fed via the X2 interface to this coordinator. However, in many cases, the X2 interface is directly used to connect two neighboring small cells when they need to make a localized control decision such as handovers. So the LTE control plane is hybrid; distributed for certain functions (handovers) and logically centralized for some others (interference, load management etc.). In this paper we will focus on the interference management aspects of the control plane design since that is typically the most important factor that determines overall network performance and spectral efficiency.

The latency and bandwidth of the control plane is therefore dictated primarily by the quality of the backhaul link technology and network used to connect the BSes to the packet core network. While operators typically invest significantly in providing macro BS with dedicated fiber backhaul, they cannot do so for small cells because of their smaller coverage area. The economics of a small cell (in terms of its coverage area and the number of users it can support at any time) does not justify deploying dedicated fiber links to each cell. Further small cells are often deployed in urban hotspots (e.g. bus stops, concerts, downtown etc) where digging and deploying fiber is prohibitively expensive or not possible due to city regulations. Hence operators are forced to use any available backhaul including cable connections, DSL lines etc that are leased from another network operator such as Comcast. The IP latency of these links from any small cell BS to a neighboring BS or to the macro coordinator is on the order of 20-30ms. Bandwidth is typically not an issue since these links are capable of providing 100Mbps speeds which is sufficient for LTE small cells.

Some companies have recently proposed using microwave frequencies (5-10GHz) for building point to point backhaul links. However typically these links do not work well for small cell deployments in urban areas. Most city areas where one might deploy a small cell are likely to be concrete jungles, with no direct line of sight path available between neighboring small cells or to the macro eNB. Without LOS, links built on these higher frequencies do not work well since signals at these frequencies do not travel through walls and lose a lot of strength upon reflection.

2.2 Interference Management in the LTE Control Plane

While deploying small cells is becoming increasingly necessary to keep up with the ever-increasing demand for capacity, more small cells also means more cell-edges in the network and therefore more problems of inter-cell interference given that LTE is designed for a frequency reuse of 1. LTE and LTE-Advanced (LTE-A) specify several schemes for interference management, each requiring varying degrees of coordination between neighboring base stations and thereby having different latency and bandwidth requirements over the control plane.

Inter-Cell Interference Coordination (ICIC) is specified in Releases 8/9 and involves frequency and power domain coordination whereby certain resource blocks are avoided by one cell (or used to serve core users at lower powers) so that they can be used by the edge users of neighboring cells. ICIC requires semi-static coordination on the order of a few seconds and is not sensitive to control plane latencies that is on the order of tens of milliseconds, and also has negligible bandwidth requirements compared to, for example, handover [10]. Recently, ICIC has been extended to time domain in enhanced Inter-Cell Interference Coordination (eICIC) wherein the macrocell stops using the traffic channel in Almost Blank Subframes (ABS) (but keeps broadcasting essential signaling and information at very low power), thereby allowing small cells to serve those UEs who would have otherwise experienced strong interference from the macrocell. Depending on the data traffic demand, the ABS pattern needs to be coordinated on the order of 40ms [5].

In Release 9, the semi-static coordination in ICIC is enhanced to dynamic coordination in Coordinated Multi-Point (CoMP) where resources can be coordinated as rapidly as on a per 1ms sub-frame basis. One form of CoMP is Coordinated Scheduling/Beamforming (CS/CB) where neighboring cells coordinate user scheduling and beamforming decisions with each other. The more attractive form of CoMP is Joint Transmission (JT), a sub-category of Joint Processing where data to a single UE is transmitted from multiple cells to improve the received signal quality and/or actively cancel interference for other UEs. To do so, the cells have to exchange channel state information (CSI) from each cell to each UE.
for which transmissions are being coordinated, and then calculate the precoding vectors to use. CoMP requires significantly more backhaul bandwidth - one estimate suggests 770kbps of control information per X2 interface between tri-cell base stations coordinating every 1ms in CS/CB, and several Mbps more of forwarded user data in JT [11] - as well as a lower control plane latency on the order of a millisecond, and also requires tight synchronization between the coordinating base stations.

It is important to mention here that while ICIC, eICIC and CS/CB essentially try to avoid or reduce interference, CoMP-JT tries to exploit the interfering links to provide capacity gains over other schemes. So ideally, operators want to use CoMP-JT and achieve the higher capacity gains. In the next section, we discuss the impact of the practical control plane latencies on the performance of interference management and specifically CoMP [1] to motivate the need for a low-latency control plane.

3. IS THE CURRENT CONTROL PLANE SUFFICIENT FOR LTE?

In this section, we show via detailed simulations and analysis that the current LTE control plane design is incapable of scaling to meet the control signaling needs for dense small cell heterogeneous networks. As described in the previous section, in current deployments, the control plane latency is on the order of tens of milliseconds, whereas bandwidth is plentiful (around 100Mbps or more). We show that with such latencies, control plane functionality such as CoMP for managing interference would work poorly and in fact hurt the performance of the network. Intuitively, the reason is the coherence time of the channels. An empirical estimate of the 90% coherence time for an urban outdoor user walking at 5kmph is 4-5ms [13], a fact that is corroborated by [14]. Thus, a 10ms latency implies that the shared channel state information (CSI) is only about 80% correlated with the true channel by the time it is transported over the X2 control interface. We find that such staleness in CSI causes the average network capacity with CoMP to drop by as much as 40% or more and is in fact worse than doing nothing (i.e. ignoring interference) for core users and avoiding interference (i.e. by time-division) for edge users. We briefly present our findings below.

3.1 Impact of control plane latency

We consider an urban microcell deployment and focus on the canonical 3-cell topology shown in Figure 1 with 3 mobile clients, one per each cell, that are being served at any time. We use a MATLAB implementation [14] of the 3GPP Spatial Channel Model (SCM) [15] for generating the time-varying $3 \times 3$ channel matrices. The simulation parameters are summarized in Table 4. The coordination-based joint transmission procedure (CoMP-JT) is summarized in Figure 2. The coordination mechanism is abstracted out in Step 2 of the figure - the design of the coordination plane will be the focus of the next section, all that matters for the analysis in this section is the coordination latency $L$ which is treated as a variable. We make use of a practical and nearly optimal soft interference nulling precoder [12] to precode user data before joint transmission.

![Figure 1: A 3 x 3 urban microcell cluster](image)

![Figure 2: CoMP Joint Transmission](image)

Figure 3 shows the average capacity scaling for different latencies as a function of the number of uniformly spaced microcells required to cover a circular region of 2km radius. In other words, the horizontal axis represents decreasing microcell radii which is a proxy for increasing density. Note that these latencies represent the total delay between the time the channels are estimated and the time they are used for precoding and transmission, and are usually at least 1ms higher than the control plane latency due to the feedback and other processing delays in between (so the Latency = 1ms curve actually represents a zero-latency control plane and so on).

The small cell industry expects a linear increase in network capacity with the addition of each small cell base station. With interference coordination techniques like CoMP, as the Latency = 0-2ms curves show us, the linear scaling is indeed possible with near-instantaneous coordination (the scaling is actually more than linear because cell splitting provides significant diversity gains in addition to linear multiplexing gains). However, the capacity scaling drops very
quickly with density as the total latency exceeds 5ms. Specifically, for the parameters used in this simulation, we find that the average network capacity drops by as much as 40% when the total latency is 10ms and 50% when it is 20ms.

We explore another question - does coordination at higher latencies provide any gain at all over the simpler techniques of ignoring or avoiding interference? If yes, how do these gains vary with user location (cell-core vs cell-edge)? In order to find an answer, we zoom into a specific microcell of radius 200m and evaluate the average capacity achievable with CoMP-JT for different coordination latencies as well as with IGNORE (i.e. treat interference as noise) and AVOID (i.e. time division between the base stations). Figure 4 plots the different average capacities per cell normalized by the average AVOID capacity at each user location when the users are symmetrically moved along the dotted lines in Figure 1.

Qualitatively, we observe that (1) the gains from coordination are significant only for edge users while IGNORE works almost as well for the core users. This makes sense because core users anyway see negligible interference (as compared to the direct signal strength), so coordinating with the neighboring base stations does not provide significant benefits. (2) when the coordination latency is too high, the simpler technique of AVOID outperforms CoMP for edge-users. (3) while coordination holds great potential for improving cell-edge throughput, it is also at the cell-edge where it is the most vulnerable to latency, indicated by the largest percentage drop from the zero-latency capacity. Conceptually, this happens because the interfering links are the strongest at the edge, so any error due to staleness shows up as a large increase in the effective noise floor (the next subsection makes this notion clearer).

These observations and results collectively tell us that (1) interference management techniques based on dynamic coordination, like CoMP-JT, can help us realize the promise of linear network capacity increase with small cells, and (2) in order to extract the maximum value out of such techniques, the coordination latency inevitably needs to be on the order of a 2-3 milliseconds (the lower the better).

Impact of coordination latency: An analytical view

One might wonder if the drastic impact of coordination latency illustrated in the previous subsection is an artifact of the specific choice of simulation parameters. It is not. In this subsection, we argue analytically that such performance limits are in fact fundamental to dense urban networks.

In order to analyze the impact of coordination latency, we need a model for how the channels change over time. We adopt a correlated block fading channel model as described below. Such a model, in addition to being analytically tractable, captures the one essential piece needed to understand the impact of coordination latency - the correlation between the current and the delayed CSI.

Let $T_c(\rho)$ denote the $\rho \%$-coherence time of a single-tap channel (an OFDM sub-channel is effectively single-tap). The correlated block fading model assumes that the channel stays constant over a period of one $T_c(\rho)$, referred to as a slot, and changes with correlation $\rho$ at the beginning of the next slot. Therefore,

$$h_{T_c(\rho)} = \rho \cdot h_0 + z_{T_c(\rho)}, |\rho| \leq 1$$ (1)

where $z_{T_c(\rho)}$ is independent of $h_0$ and $E[z_{T_c(\rho)}] = 0$ given that the complex baseband channels are zero-mean at all times. Assuming the channel is wide sense stationary, if $\sigma_h^2 \triangleq E[|h_0|^2]$, we must have $E[|h_{T_c(\rho)}|^2] = E[|h_0|^2]$, and therefore $E[|z_{T_c(\rho)}|^2] = (1-\rho^2)\sigma_h^2$. Note that $\rho$ is a parameter of this block fading model and controls the granularity of discretizing the continuous-time channel - the closer $\rho$ is chosen to 1, the smaller will be $T_c(\rho)$ for a given channel and the finer will be the modeling of the channel variations.

Using this model, if $L$ represents the latency of coordination between any pair of base stations (in order to keep the expressions simple, we will consider $L$ in multiples of $T_c(\rho)$), then the channel $h_{Lt}$ at $t = L$ is related to the chan-
nel $h_0$ shared at $t = 0$ as

$$h_L = \rho^{L/T_c(\rho)} h_0 + z_L$$

where $E[|z_L|^2] = (1 - \rho^{2L/T_c(\rho)}) \sigma^2_h$.

The term $\rho_L \triangleq \rho^{L/T_c(\rho)}$ represents the channel correlation across a time interval $\Delta t = L$ and measures how correlated the stale CSI is to the actual channel at $t = L$. Let us define $S_L \triangleq (1 - \rho_L)$ as the staleness at $t = L$ of the CSI that was shared at $t = 0$. As an example, if the current channel is 90% correlated with the channel at some previous time, then by the above definition the previous CSI will be said to be 10% stale currently. The variance of the error due to staleness can thus be expressed as $(1 - (1 - S_L)^2)\sigma^2_h$.

Now we are all set to argue why the impact of a given coordination latency $L$ is much more pronounced in dense urban networks. In urban areas, the coherence times are typically smaller due to the inherent dynamism in the environment itself, which means that for a given $L$, the staleness $S_L = 1 - \rho^{L/T_c(\rho)}$ ($|\rho| \leq 1$) is higher. In addition, if the network is dense, the links are typically stronger (since the clients are closer to the base stations), and hence $\sigma^2_h$ is higher.

Therefore, in dense and urban networks, the problem gets compounded and the error $(1 - (1 - S_L)^2)\sigma^2_h$ due to a given latency $L$ is much higher. As the network becomes denser, the higher errors in CSI lead to higher errors in the precoding vectors which in turn lead to the huge capacity drops that we saw earlier in Figures 3 and 4.

We would also like to clarify here that, for example, a 10% staleness (or equivalently, 90% correlation) is not the same as a 10% error in channel coefficients. As we explained above, a 10% staleness actually results in a $(1 - (1 - 0.1)^2)$ or 19% error relative to the channel coefficients.

4. DESIGN

SwiftC is a control plane design for heterogeneous and dense cellular networks consisting of macro and small cells capable of providing moderate bandwidths (on the order of an Mbps) at very low latencies (on the order of a millisecond). Its main component is a novel design for low-latency physical backhaul connectivity to the macro base station for control signaling that enables the use of CoMP and other latency-sensitive network management mechanisms.

SwiftC’s key architectural insight is to physically decouple the LTE data and control planes in the backhaul. As we saw before, the LTE control plane requires extremely low latencies on the order of 2-3 ms, but is not bandwidth intensive. The LTE data plane on the other hand is less latency sensitive (latencies on the order of 20-30ms are fine for most data traffic and even VoLTE voice calls), but is quite bandwidth sensitive (requires several hundreds of Mbps backhaul connectivity). By physically coupling the data and control planes (i.e. using the same physical backhaul connectivity) and layering both control and data signaling on top, we end up with a situation where the small cell backhaul has to provide both very high bandwidth and extremely low latency. Such a stringent requirement limits the backhaul options available to operators, they are forced to use direct fiber links since thats the only technology that can provide the combination of high bandwidth, low latency and reliability that LTE networks need. Such fiber deployments however are prohibitively expensive (imagine deploying fiber in an urban environment such as Manhattan), and have prevented small cell deployments from happening at scale.

SwiftC physically decouples the LTE data and control planes. The key insight is to use the existing LTE macro network itself as the physical layer technology for control plane backhaul. In other words, SwiftC’s control plane signaling happens on LTE frequencies itself between the macrocell and the small cells. By doing so, small cells gain a direct connection to the macro-cell control plane coordinator and an extremely low latency link (on the order of 2-3ms). Operators are then free to choose data plane backhaul that is high bandwidth but doesn’t have to satisfy the stringent latency requirements. Such backhaul options are more easily available in the form of cable networks, ADSL and even public fiber networks switched over another operator’s wireline networks.

SwiftC does not require additional frequency bands as it creates a control plane within the LTE spectrum itself. However the challenge is that we may now be using extremely scarce and expensive LTE spectrum for control signaling. The key contribution of this paper is a design that enables a very efficient control plane design using existing LTE spectrum.

SwiftC’s control plane logical architecture is similar to current LTE deployments and hence it can be easily deployed. As before each small cell connects to a logically centralized coordinator which is deployed at the macrocell within whose coverage area the small cells are located. The small cells use SwiftC to send and receive control signals from the coordinator. The coordinator is responsible for making all radio network management decisions.

4.1 SwiftC Backhaul Design

The key idea in designing SwiftC’s control plane backhaul is to use the existing LTE spectrum itself for control signaling with the macro. In other words, each small cell sends and receives control messages (such as channel state measurements, decisions on which small cells should coordinate using CoMP and how etc.) to and from the coordinating macro on the same LTE spectrum that is used for data transmission. To implement this, each small cell is equipped with a UE (phone) radio, which it uses to connect with the macro base station just like any other phone. It uses this connection to send and receive control messages.

Such a design has several attractive properties. First it is extremely simple to deploy, since a macro network is already architected to talk to phones, adding control links to each small cell is trivial. Second, it works quite well in urban non line-of-sight environments because it uses LTE frequencies
and physical layer protocols which were designed to work well in such environments. Further it requires no additional spectrum unlike other microwave backhaul based solutions.

A natural question however is whether we are using valuable LTE spectrum for control signaling. To see why this might happen, we have to look at how an LTE small cell operates. We focus on LTE FDD (frequency division duplexing) [5] small cells in this paper, but the same arguments apply for TDD LTE (Time Division Duplexing). FDD LTE has two frequencies, one for the uplink which is used by the UEs to transmit to the eNB (both macro and small cells), and the other is the downlink which is used by the eNB to transmit to the UEs. However with SwiftC’s design, a small cell eNB also acts as a phone which connects to the macro eNB. This implies that the small cell may have to transmit on the uplink frequency to the macro eNB while it is receiving data from the UEs that are connected to it on the same uplink frequency, and the reverse on the downlink frequency.

A natural design choice is to separate the control transmissions/receptions from the small cell eNB to the macro in time with the data transmissions/receptions from the UEs connected to the small cell. In other words turn the small cell into a half duplex LTE mesh node to coordinate transmit and receive. However this can be extremely wasteful. For example to implement CoMP in an urban deployment, small cells have to exchange channel state information with the macro eNB at a rate of 5Mbps or so (assuming walking mobility and the need to send updates at least every 2ms). While the small cell is sending this information to the macro eNB, it cannot receive from its own UEs and throughput is significantly reduced. In fact, we find that sending such control information means that the small cell cannot listen to its own UEs for 25% of the time. Further such scheduling in the small cell is extremely complex to build because in effect the small cell has to schedule its own transmissions and receptions around when the macro eNB schedules the small cell to transmit/receive control messages to/from it.

Our key innovation is to leverage recent work on full duplex radios to turn each small cell into a dual full-duplex radio that can act simultaneously as an eNB (to its clients) and UE (to a macro eNB), see Figure 5. In other words, a small cell equipped with SwiftC would be able to send control information to a macro eNB while listening to its own clients on the uplink, and at the same time would also be able to receive control signals from the macro eNB while serving its own UEs on the downlink. Thus, the SwiftC control plane can effectively coexist with the small cell user plane without hurting its capacity. In order to enable this coexistence, SwiftC must cancel the self-interference caused by the transmission of the small cell eNB at its UE receiver (i.e., on the downlink), and similarly the transmission of its UE at its eNB receiver (i.e., on the uplink), as shown in Figure 5.

**How much self-interference cancellation is needed?**

Each of the uplink and downlink self-interference canceling units must be able to reduce the maximum transmit power to the noise floor at the corresponding receiver over the entire bandwidth of operation (any residual interference below the noise floor does not affect performance). Consequently, the total self-interference cancellation required for each Tx-Rx pair i.e., uplink Tx-Rx and downlink Tx-Rx, is the difference between the maximum Tx power and the Rx noise floor (expressed in dBm).

**Rx noise floor:** The receiver noise floor depends on the bandwidth B and the noise figure NF of the receiver, and can be estimated as \(-174 + 10 \log_{10}(B) + NF\) (in dB), see Table 2.

### Table 2: Typical receiver noise floors

| Receiver | NF | 5MHz | 10MHz | 20MHz |
|----------|----|------|-------|-------|
| Small cell eNB | 5dB | -102 | -99 | -96 |
| Small cell UE | 9dB* | -98 | -95 | -92 |

*assuming it to be the same as for a conventional UE

**Max Tx power:** First, on the uplink, we observe that a small cell UE can be expected to experience much lower path losses to a macro eNB than a conventional UE since it would typically be located 10m or higher above the ground, and can therefore afford to transmit at a lower power. In fact, using the 3GPP Spatial Channel Model (SCM) [15], we find that the channels seen by an urban microcell UE (12.5m high) located at the edge of a 1km-radius macrocell (32m high) can be expected to be as much as 30dB stronger on average than by a conventional UE (1.5m high) at the same distance, see...
Figure 4 (Left). We also find that at 23dBm, the maximum specified Tx power for UEs, the Rx SNR at the macro eNB is nearly 50% likely to be in excess of the maximum useful SNR (~18dB, corresponding to the highest MCS for uplink i.e., 64QAM and 0.85 code), thereby leading to a wastage of power, see Figure 5 (Right). Instead, if the small cell UE lowers its Tx power by 5dB, it can reduce the likelihood of power wastage by 25% and yet stay connected for more than 95% of the time (note that these are the worst case estimates - the small cell is located farthest from the macrocell). Thus a practical estimate for the maximum Tx power of a small cell UE is 18dBm.

Second, on the downlink, we believe the expected transmit power used will be around 30dBm. The reason is that typical small cell deployments are for covering hotspots such as bus-stops, and hence the coverage area required is small. Further small cells are expected to be deployed on light poles, walls etc, and hence cannot afford to be big and heavy. Using transmit powers higher than 30dBm results in big and hot power amplifiers that require large boxes to cool them and make it infeasible to build a “small” cell. Therefore most actual small cell deployments will have compact base stations that have a transmit power around 30dBm (1 watt).

![Figure 6: (Left) An illustration of channel gains seen by a small cell UE (12.5m high) and a conventional UE (1.5m high) to a macro eNB (32m high) located 1km away. (Right) Cdf of Rx SNR at the macro eNB for two different small cell UE Tx powers (23dBm and 18dBm).](image)

Table 3 summarizes the self-interference cancellation requirements for SwiftC. It is important to mention here that although wider bandwidth systems require lesser cancellation owing to their higher noise floor, in practice it is more difficult to match the cancellation blocks over wider bandwidths and hence, self-interference cancellation is practically much harder in wider bandwidth systems.

| Band | Max P_{transmit} | Cancellation required (in dB) |
|------|------------------|-------------------------------|
| Uplink | 18dBm | 120 117 114 |
| Downlink | 30dBm* | 128 125 122 |

*assuming the small cell is a microcell

Table 3: SwiftC: Cancellation requirements

SwiftC leverages recent work on full-duplex radios [17] and employs a combination of analog and digital cancellation blocks to provide the required self-interference cancellation on both uplink and downlink frequencies. In a nutshell, the self-interference in each Tx-Rx pair consists of (1) about 65-70dB of transmitter (broadband) noise generated by the components of the analog RF Tx front end, which must be necessarily canceled in the analog domain (by taking a copy from where it is generated), and (2) about 50-55dB of the remaining Tx signal which consists of nearly 20dB of residual non-linearities (after analog cancellation) and 30-35 dB of linear components, and can be canceled in the digital domain. We refer the readers to [17] for the details of the algorithms used to design the analog and the digital cancellation blocks that can meet the above requirements. In Section 5 we build a prototype and demonstrate that SwiftC can indeed provide the required self-interference cancellation with only a marginal (1.7dB) increase in noise floor.

4.2 Increasing efficiency

One of the major concerns with SwiftC is whether it expends a lot of scarce LTE spectrum for coordination. We have described how SwiftC can leverage full duplex radios to ensure that no capacity is lost at the small cell. However, SwiftC does consume some macrocell resources both on the uplink and the downlink, and addressing this overhead is a key aspect in the design of SwiftC. In the following discussion, we show how we can exploit the properties of SwiftC’s physical backhaul medium itself, namely the LTE physical layer, to increase the efficiency of SwiftC.

How can we optimize the overhead on macro resources?

First, we note that the channels a macro eNB would see to the small cell UEs over SwiftC can be expected to be much more static and of much better quality than to mobile UEs located at comparable distances. This is because the small cells are typically installed 10m or higher above the ground and hence their path losses are significantly lower [15], see Figure 6 (Left). In addition to making a case for introducing higher modulation and coding schemes for this special category of small cell UEs to exploit the naturally good channel quality, this offers the advantage of requiring much lesser time-frequency resources for communicating a given amount of control information. For e.g., using 3GPP SCM [15], we find that from the perspective of a macrocell, providing 1 Mbps of average uplink throughput to a small cell UE located at the edge (1km away) is equivalent to denying only 183.4 Kbps of uplink throughput to a UE located just 500m away and just 39.0 Kbps to a UE located at the cell-edge. Thus, using the wireless physical layer as the backhaul medium works to SwiftC’s advantage by lowering the effective overhead it incurs on macrocell capacity.

![Figure 6: Channel gains seen by a small cell UE (12.5m high) and a conventional UE (1.5m high) to a macro eNB (32m high) located 1km away.](image)
Second, we observe that depending on the control information, which mostly relates to some form of channel state information (recall that SwiftC is intended for communicating control information that changes on the order of 1ms), there exists a scope for exploiting redundancies in the control information itself to optimize the overhead. For example, when a small cell has to forward the CSI of its clients over an LTE resource block (consisting of 12 sub-channels) to the macro coordinator, it can exploit the strong correlation between the narrow-band LTE sub-channels (∼15kHz) to compress the information. Similarly, even though the channels decorrelate much faster over time in dense urban environments, we find that non-trivial compression can also be achieved across time by scheduling clients over consecutive sub-frames on the same sub-channels.

In essence, if \( \mathbf{h}^T = [h_0, h_2, \ldots, h_{N-1}] \) represents the channel coefficients seen by a client to a small cell eNB across \( N \) consecutive sub-channels in a given sub-frame (or \( N \) consecutive sub-frames over a given sub-channel), then the small cells can transform \( \mathbf{h} \) into another domain using an appropriate sparsity transform \( T \) such that the resulting sequence \( \tilde{\mathbf{h}} = Th \) is sparse. As a result, \( \tilde{\mathbf{h}} \) can be represented using much fewer bits than \( \mathbf{h} \) for a given level of distortion. Note that these compressions can also be performed for SwiftC by the clients themselves before feeding back their CSI to the small cells, but that might require firmware changes to the current LTE UEs. Since we want to keep the design of SwiftC independent of UEs, we let the small cells optimize the representation of the control information before sending over SwiftC.

Although we do not deal with optimal sparsity transforms in this paper, we show in Section 5 that the following simple and practical encoding scheme can reduce the overhead of SwiftC to a negligible fraction of the macrocells capacity on the uplink. If \( q \) bits of magnitude and \( q \) bits of phase are required to reliably represent a channel coefficient, the Channel Quality Indicator CQI and Channel Phase Indicator CPI can belong to one of \( 2^q \) quantization levels. In order to encode and send each coefficient along consecutive sub-channels or sub-frames, send the first coefficient of the series \( h_0 \) using \( q + q \) bits, and then send the CQI of subsequent coefficient \( h_n \) as (1) bit 0, if \( \text{CQI}_n = \text{CQI}_{n-1} \), (2) bits 10, if \( \text{CQI}_n - \text{CQI}_{n-1} = -1 \), (3) bits 11, if \( \text{CQI}_n - \text{CQI}_{n-1} = 1 \), or (4) \( q \) bits otherwise (and similarly for CPI).

This scheme essentially encodes the increment using Huffman coding if the increment is within one quantization level, otherwise it refreshes it i.e., sends the full \( 2q \) bits for the coefficient. In Section 5, we show that this scheme works very well in practice because for typical LTE OFDM channels, the increments over one sub-channel or sub-frame is less than one quantization level with a very high probability (with an increment of 0 being more likely than an increment of ±1).

In addition, we note that there typically exists significant intra-site correlation between the channels of a user to the different antennas of a small cell as well as inter-site correlation between the channels seen to neighboring cells [15], which can be exploited similarly for lowering the overhead further, if needed.

Also, we note that the control information on the downlink will usually be a few bits per interface per sub-frame, usually representing a decision index or a network state indicator, for e.g. PMI for interference management. Combined with the facts that a macro eNB typically has a much larger transmit SNR and sees very strong channels to the small cell UEs, we believe that SwiftC will have a negligible impact on the overall downlink capacity of the macrocell.

### 4.3 Illustration: Interference management with SwiftC

Now that we have described the design of SwiftC, we take up a typical example of a dense cellular network consisting of a macrocell and several smalls and illustrate how SwiftC can be used for interference coordination in small cells.

![Image](image_url)
microcells and see strong interference from their neighboring micro eNBs. Client C lies in the core of microcell 3 but might be seeing strong interference from the macro eNB. Client D is a high mobility client who happens to be within the coverage area of microcell 2 at this instant.

A typical network interference management scheme might choose to

1. let client D be served by the macro eNB even though it lies within the microcell cluster since it is not going to stay in the cluster for long anyway.
2. let client C be served by microcell 3, and AVOID or reduce interference from the macro eNB (for e.g., eICIC) if its interference is strong, otherwise IGNORE interference.
3. EXPLOIT interference for client A using CoMP joint transmission by microcells 1 and 2.
4. EXPLOIT interference for client B using CoMP joint transmission by all three microcells.

While clients C and D can be served with little or no control signaling between the different eNBs, the microcells need to coordinate on the order of a millisecond to serve clients A and B using CoMP. If the microcells are equipped with SwiftC, this low-latency coordination is simple to execute. Figure 9 summarizes the coordination mechanism for a $2 \times 2$ scenario. (a) The clients report to their serving micro eNBs on the uplink their respective channels to the two micro eNBs. (b) The micro UEs process and forward the compressed CSI via SwiftC on the uplink. The macro eNB replies back with coordination parameters (PMI, powers, schedules etc.) on the downlink. All this time while the micro UE is communicating with the macro eNB, SwiftC’s self-interference cancellation blocks ensure that the micro eNB can keep communicating with its other clients as usual both on the uplink and the downlink. (c) The micro eNBs precode and jointly transmit to the clients on the downlink.

Since SwiftC uses LTE data channels to carry control traffic, it inherits the user-plane latency that LTE itself guarantees. However, there are a few significant differences that promise to make SwiftC’s latency guarantees even better. First, since SwiftC carries critical control information, the macro eNB can prioritize this traffic including pre-allocating resource blocks, which would mean lesser processing delays and lesser waiting times. Consequently, SwiftC can provide a best-case one-way latency of 1 TTI (Transmission Time Interval), which is 1ms in current LTE standards, and an average one-way latency of 1.5 TTIs that includes an average waiting time of 0.5 TTI until the start of the next sub-frame. Second, as the wireless channel that SwiftC operates over is significantly stronger (owing to lower path losses at the heights at which small cells are typically installed), SwiftC traffic can be expected to suffer lesser re-transmissions and can consequently guarantee a better average latency. Third, our simulations have shown the typical control packets to be lesser than 0.5ms in duration, so the latency of SwiftC is largely limited by the TTI defined in current standards and will automatically improve as the standards evolve to support shorter transmissions.

Since one use of the control plane involves one use each of SwiftC’s uplink and downlink, SwiftC can provide a best-case latency of 2 TTIs (= 2ms in current standards) and an average two-way latency of 3 TTIs. The total coordination latency however includes the sum of the feedback and processing delays, and can be expected to be 1-2ms higher. Figure 10 shows a typical coordination timeline for the example illustrated in Figure 9.

Figure 10: Example of a coordination timeline (cf. Figure 9).

5. EVALUATION

In this section, we

1. design a prototype of SwiftC’s backhaul and demonstrate that it can provide the highest self-interference cancellation required at the widest bandwidth supported by LTE (namely 122dB at 20MHz).
2. evaluate the bandwidth requirements of the SwiftC plane and show that it translates to a negligible overhead in terms of the overall macro capacity.

3. simulate the performance of interference coordination techniques such as CoMP in a dense LTE macrocell (containing several microcells) and show that the overall network capacity using SwiftC can scale linearly with density ($N \times$ increase with $N$ small cells), something that the current X2 over IP control planes fall way short of providing.

5.1 Implementation of SwiftC

We design and build a prototype of SwiftC to evaluate its novel physical backhaul design for the LTE control plane. The goal is to show that it is possible to implement a full duplex LTE small cell that connects to the macro cell as a UE for sending and receiving control plane traffic. The primary determinant of this is whether SwiftC can implement the self-interference cancellation needed to build the full duplex capability with the small cell eNB and the UE.

To experimentally verify this, we build a prototype with the following components, see Figure 11:

- a \textit{transmitter} (implemented using a vector signal generator) that transmits standard OFDM signals at 2.4GHz over 20MHz, the widest bandwidth that LTE supports.
- an \textit{RF power amplifier} that boosts the transmit power to 30dBm, the maximum that a SwiftC-equipped small cell radio is expected to transmit at.
- a \textit{Tx antenna} and an \textit{Rx antenna} that act as the SwiftC Tx-Rx pair, and correspond respectively to the antennas on the small UE radio and the small cell eNB radio on the uplink and vice-versa on the downlink.
- an \textit{analog cancellation board} which implements fixed delay lines and programmable attenuators that can execute the analog cancellation algorithm proposed in [17].
- a \textit{receiver} (implemented by a spectrum analyzer) that converts the analog received signal into digital I-Q samples. The widely-used software radios such as USRPs and WARP typically have very poor noise floors ($\sim -85$dBm over 20MHz) and do not let us demonstrate the functioning of SwiftC for typical UE and eNB radios whose noise floors are at least 5-7dB better, see Table 2. Therefore we use a commercial radio test equipment (-90dBm noise floor at 20MHz) for implementing our receiver.
- a \textit{digital cancellation block} implemented in software (MATLAB) using the algorithm proposed in [17] that acts on I-Q samples from the spectrum analyzer.

Our goal here is to show that SwiftC can provide the required self-interference cancellation required on both uplink and downlink over the widest bandwidth (20MHz) that LTE supports. Note that self-interference cancellation is more difficult when the bandwidth is larger since matching the response of the cancellation blocks to wider bandwidths is practically much harder.

Figure 12 shows the cancellation performance of our prototype. The transmit signal is a standard LTE-like OFDM signal at 2.4GHz and 32dBm (35dBm at power amplifier output followed by a 3dB cable loss). The analog cancellation board reduces the signal to -40dBm (72dBm cancellation) while the digital cancellation board clears up another 50dB of self-interference to reduce it to the noise floor. The result is 122dB of total cancellation, the maximum that SwiftC needs to provide at 20MHz, see Table 3. The effective increase in noise floor, as measured from the samples after digital cancellation, is 1.7dB.

Note that the cancellation requirement on the uplink is smaller (only 114dB at 20MHz) and can be achieved by this same setup, although we omit any experimental results for the uplink since our radio test equipment cannot emulate the noise floors of commercial eNB radios. In the rest of this section, we treat the self-interference cancellation blocks as a blackbox that raises by the noise floor at the small cell eNB and the small cell UE radios by 1.7dB. Next we turn to simulations to evaluate the performance of the SwiftC control plane in practical LTE small cell deployments. The simulations use the same deployment conditions and channel models that are used by the LTE standards body to evaluate new proposals for standardization, and hence are considered to be quite representative. Further, its infeasible except for the largest operators to actually be able to deploy a full scale sys-

Figure 11: Experimental setup of a SwiftC Tx-Rx pair.

Figure 12: Self-interference cancellation provided by SwiftC prototype. The 32dBm transmit signal over 20MHz is reduced in steps by 72dB (analog cancellation) and 50dB (digital cancellation) to the noise floor at -90dBm.
ten implementation of SwiftC and evaluate it under realistic conditions. Hence we turn to detailed simulations.

5.2 SwiftC benchmarks

In this subsection, we benchmark SwiftC on the following two aspects.

1. How much control traffic does SwiftC need to support, assuming that resources would need to be coordinated on per 1ms sub-frame basis and that CSI is going to be the dominant form of control information? (Section 5.2.1)

2. What overhead does this traffic incur on the uplink capacity of the macrocell? (Section 5.2.2)

5.2.1 Bandwidth requirements

In order to estimate the bandwidth requirements of SwiftC, we analyze from the perspective of a single small cell. A small cell serves its clients by allocating each of them one or more resource blocks (RBs), each consisting of 12 sub-channels, for one or more sub-frames.

Let us look at how many bits would be needed to represent the channel state information of a client over an RB in each sub-frame (i.e., per eNB-UE antenna pair). Each channel coefficient can be reliably represented using 6 magnitude bits and 6 phase bits, i.e. the channel quality indicator (CQI) and the channel phase indicator (CPI) each belongs to one of 64 levels (current LTE systems use a 4-bit CQI feedback, but we have observed that advanced functions like CoMP need a more precise representation in order to avoid precoding errors). Consequently, we need 12 × 12 uncompressed bits to represent the channel coefficients per RB per 1ms, which translates to a rate of 144Kbps for one RB and 14.4Mbps for a 20MHz LTE system (100 RBs). This is of course too high a requirement from a single small cell (note that a macrocell would need to support several such small cells within each sector) and needs to be reduced in a way that does not affect the quality of control information.

As a result, the total requirement over SwiftC can be expected to be around 10Kbps per RB. Since each small cell is expected to share the channels seen by each of its clients not just to itself but also to at least 1-2 neighboring cells and assuming each small cell would need coordination for ~ 50% of its radio resources (the remaining resources would typically be used with IGNORE for core users or AVOID i.e., eICIC, with the macro), the effective required rate is going to be ~ 3 × 0.5 × 10 Kbps per RB. This means that at the highest rate of coordination (i.e., per 1ms) with up to 2 neighbors for each client and for carrying full resolution channel state information without any increase in distortion, SwiftC would need to support about 15Kbps per RB, or equivalently 1.5Mbps over 20MHz. The above analysis is for the average case scenario. In the worst case scenario, the control signaling rate would be a factor of two higher since that corresponds to using coordination over the entire set of resource blocks.

Due to its full duplex nature, having to send such control signaling traffic to the macrocell from the small cell has almost no impact on the small cell’s capacity itself, we are getting this control signaling for free by transmitting at the same time the small cell is receiving on the uplink frequency. However we do consume macrocell resources, whose impact we quantify next.

5.2.2 Impact on macrocell capacity

A single macrocell can be expected to cover 4 or more small cells within each sector, so the total uplink capacity that it needs to provide for SwiftC can be expected to be in
excess of 6Mbps. Does that mean SwiftC robs 6Mbps or more of uplink capacity straight from the UEs who could have otherwise used the resources in SwiftC’s absence? The answer is not really, and the reason as we had mentioned in Section 4.2 is that the small cell UEs typically see much stronger and static channels, and can very often operate at the highest modulation and coding rate even when deployed at the edge of the macrocell, while the corresponding rates over the same time-frequency resources are much lower for UEs located closer to the ground. Figure 15 shows the average loss in the capacity of an UE connected to the macrocell, and located at 500m and 1000m away, as a function of the capacity requirements of SwiftC. For e.g., even for an UE located in the core of the macrocell, providing 6Mbps on the uplink to SwiftC is equivalent to denying only 1.1Mbps to the UE.

Figure 15: Average loss of uplink capacity for an UE connected to the macrocell as a function of the SwiftC capacity requirements.

The main takeaway from this analysis is that although SwiftC requires to carry control traffic on the order of several hundreds of Kbps or even a few Mbps on the data channels of the macrocell, the impact on the UE uplink throughput is much lesser.

5.3 Interference management with SwiftC

In order to demonstrate the interference coordination benefits that SwiftC can provide, we simulate an urban hetnet consisting of a macrocell of 1km radius and a variable number of microcells deployed within the coverage area of the macrocell. The simulation parameters are summarized in Table 4. We generate 1000 users over the region distributed uniformly at random, and randomly assign them a velocity out of 1kmph, 5kmph and 30kmph (each velocity corresponds to a different coherence time and therefore sees different rates of fading). We implement a simple scheduler that works broadly as follows for each user.

- if the user is moving at 30kmph, it associates it with the macrocell irrespective of its proximity to microcells. Otherwise,
- if the strongest channel seen by the user (in terms of Rx SNR) to any eNB is at least 15 dB stronger than the second strongest, it associates the user with that eNB who serves it using IGNORE (i.e., by treating interference as noise). Else,
- if the second strongest channel is at least 15dB better than the third strongest (if not, if the third strongest is 15dB better than the 4th strongest), it associates the user with the two (or three) strongest eNBs who serve it using CoMP. Else,
- if there are four or more very strong interferers, one or more of them AVOID interference such that the rest can serve using CoMP.
- if there are multiple users associated to an eNB, it uses round-robin scheduling for serving the users.

Note that the above scheduling need not be the best way of managing interference in a network and there might optimal schedulers that can provide higher network capacities; however, our focus here is solely on demonstrating the link-level gains that coordination techniques such as CoMP can provide when they have a low-latency control plane like SwiftC at their disposal.

We use a MATLAB implementation [14] of the 3GPP Spatial Channel Model (SCM) [15] for generating the time-varying channel matrices. We use OFDM with 512 subcarriers over 5MHz, since the SCM documentation claims that the model might not be suitable for systems with wider than 5MHz bandwidths.

5.3.1 Impact on overall network capacity

In order to evaluate the impact that a low-latency control plane like SwiftC can have on the overall capacity of a network, we simulate our test macrocell network with increasing number of microcells (2-7) deployed per sector. We compare the performance of a hetnet using the SwiftC plane for coordination with

1. an ideal network where each cell has its own piece of spectrum to operate over without causing interference to anyone else (note that coordination techniques like CoMP strive to make an interference-dominant network perform...
as if it were an ideal interference-free network). The capacity of this network benchmarks the capacity scaling that is desired out of small cell deployments.

2. A hetnet using the X2 over IP control plane. We assume that such a control plane has a one-way latency of 10ms from a small cell to the packet core network, and hence a total latency of 20ms.

Figure [15] shows the overall network capacity for the three cases (Ideal, with SwiftC, with X2 over IP) normalized by the capacity of a single macrocell network. The ideal capacity scales more than linearly (i.e., with N cells, the capacity is more than N times the capacity of a 1-cell network) due to the strong diversity gains in cell-splitting. Although the network capacity with the SwiftC plane does not provide the ideal-like diversity gains, it does result in a nearly linear capacity scaling with density (∼ 19 × with 21 small cells), something that the network with X2 over IP clearly is not capable of (only 12 × with 21 small cells).

5.3.2 Impact on coordination gains

The total network capacity includes the macrocell capacity and a component of the small cell capacity that is delivered through techniques like Ignore and Avoid which do not depend on the control plane quality. In order to scrutinize the specific impact on coordination gains that SwiftC can provide with respect to a standard X2 over IP control plane, we zoom into the component of network capacity that is delivered through CoMP transmissions. Figure [17] shows the relative gains from CoMP (as a % of the plot maximum) obtained via coordinating over (1) SwiftC and (2) X2 over IP. As the number of microcells deployed within a sector increases from 3 to 7, the CoMP gains using SwiftC relative to X2 over IP increase from 38% to 78%. Note that most of the CoMP transmissions happen for edge users who see strong interference from one or more neighboring cells, so these results also imply that the SwiftC plane can enable a significant increase in cell-edge throughput and thus effectively tackle the problem of high interference in dense networks.

6. CONCLUSION

SwiftC shows that by physically decoupling the LTE data and control planes, and by using LTE spectrum itself to implement the control plane, it is possible to design and implement sophisticated network and interference management strategies in dense LTE cellular networks. We are currently working on building a testbed that embeds SwiftC and evaluating the benefits with real-world traffic. We are also exploring how to integrate other network management functions such as load management, handoffs etc into the SwiftC control plane.

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