Abstract—The ubiquitous Ethernet has great potential of becoming an easy-to-install, cost-effective backhaul solution for mobile small cells. However, limited Ethernet bandwidth is a practical constraint. Not only is the small cell capacity limited by the Ethernet bandwidth, but also the synchronization between cells can be substantially compromised. In this article we discuss small cells with Ethernet backhaul, focusing on two practical and important aspects: backhaul bandwidth requirements, and tolerance to synchronization errors. The aspects become challenging in indoor small cell applications where the cells need to cooperatively suppress strong interference, producing a large amount of backhaul traffic. To address the challenges, we introduce a new distributed scheme of cooperative small cells over Ethernet. Exploiting a soft information combining technique, the scheme allows the signals of cooperative cells to be combined at aggregate switches along their backhaul paths, reducing backhaul traffic in Ethernet and distributing computational complexity. Our case study shows that the distributed scheme can reduce small cell backhaul traffic by 64%, compared to a conventional centralized approach. It is also tolerant to a large frequency error of ±5.0 ppm in a “free-run” state where synchronization is lost. Given the substantially reduced backhaul traffic, the new distributed scheme is able to support three times the cooperative small cells of the conventional centralized approach.

I. INTRODUCTION

Small cell wireless network architectures are important to high-density indoor environments. However, they are facing several critical challenges. One of the critical challenges is backhaul. Traditional backhaul solutions are expensive and require installation of extra cables [1]. To allow wide deployment of small cells, fast-to-install and cost-effective backhaul solutions for indoor small cells are in urgent demand. Another critical challenge lies in mitigating interference in small cells in radio-unfriendly indoor environments. Planning cell sites, arranging frequencies, and suppressing interference are complex tasks indoors. This is the result of limited inter-cell spacing, scarcity of frequency resources, ad-hoc deployment, and complicated building structures. These backhaul and interference mitigation challenges significantly impede the progress of indoor small cell deployments.

Ubiquitous availability of mature Ethernet technology is driving the development of Ethernet as a cost-effective small-cell backhaul solution. Gigabit Ethernet (with a rate of 1 Gbit/s) and 10 gigabit Ethernet, defined by IEEE 802.3-2008 standard [2], are popular in residential and enterprise venues. Studies have been conducted on small cells with Ethernet backhaul. Practicality has been verified from the perspectives of synchronization, bandwidth, and expenditure [3] in the case where cells are geographically isolated or exploit different frequencies and therefore can independently mitigate inter-cell interference. More generally, interference mitigation strategies are required for general widespread deployments.

In this article, a general practical small cell scenario with Ethernet backhaul is considered, where small cells can have overlapping coverage and spectral efficiency can be enhanced by allowing the cells to reuse the same frequency. In this scenario, the aforementioned conventional small cells with Ethernet backhaul [3] are inapplicable due to strong inter-cell interference. Small cells need to cooperate to suppress the interference and improve the throughput of users within their overlapping coverage areas. However, cooperation results in key issues of significantly increased backhaul traffic, and subsequently enlarged synchronization errors.

To address these issues, we introduce a new distributed cooperative scheme for small cells with Ethernet backhaul. The key idea is to have the small cells independently demodulate their received signals to bitwise soft information, thereby tolerating increased synchronization errors. Another critical aspect is to have the soft information of cooperative small cells combined at every switching point along the backhaul. As a result, backhaul traffic destined for the Ethernet gateway does not accumulate with the growth of Ethernet depth, and the computational complexity can be distributed to avoid congestion. A practical case study shows that the new scheme is able to reduce small cell backhaul traffic by up to 64%, compared to a conventional centralized approach. It is also tolerant to a frequency error of ±5.0 part per million (ppm) in a “free-run” state, where synchronization messages are significantly delayed or lost. Given the significantly reduced backhaul traffic, the distributed scheme can support three times as many cooperative small cells as the centralized approach.

The rest of this article is organised as follows. In Section II, a general architecture of small cells over Ethernet is presented with emphasis on Ethernet configuration and synchronization implementation. Section III first describes the conventional centralized approach of cooperative small cells over Ethernet and its challenges of increased backhaul traffic and synchronization errors. Then, we introduce the new distributed approach that addresses the challenges, followed by a comparison study between both the centralized and distributed approaches with an important fronthaul standard, Common Public Radio Interface (CPRI). In Section IV, simulation results of the approaches are provided from the aspects of small cell throughput, backhaul requirement, and tolerance to frequency errors. In Section V, a conclusion is provided.
II. ARCHITECTURE OF SMALL CELLS OVER ETHERNET

Fig. 1 illustrates a typical indoor deployment scenario of small cells over Ethernet, where 3GPP long-term evolution (LTE) small cells are considered. Every small cell base station (SCBS) is a complete base station device with functionalities of scheduling, baseband signal processing, and radio frequency generation. The SCBSs are controlled by a small cell network controller (SCNC) which routes and forwards user data, while also acting as the mobility anchor for the user plane during handover. In the context of 3GPP LTE, the SCNC can be the serving gateway of the evolved packet core (EPC), as specified by 3GPP system architecture evolution (SAE).

In the figure, Ethernet cabling is installed such that Ethernet switches on different floors are daisy chained, and computers and printers are connected to their closest switches by Categories (CAT) 5, 5e, or 6 cables on each floor. CAT 5/5e/6 can also be used to connect the SCBSs to their nearest Ethernet switches. Such a switched Ethernet structure is widely adopted in commercial and residential properties.

The figure also demonstrates the route that connects small cell traffic to the Internet; highlighted by a blue dashed line. Specifically, the traffic is sent by the SCBSs through Ethernet and metropolitan area network to the SGW/SCNC, where it is routed and forwarded through another gateway of EPC, i.e., packet data network gateway (PGW), to the Internet. For comparison, the route that Ethernet traffic travels is also demonstrated by a violet dashed line.

A key requirement of small cells over Ethernet is the Quality of Service (QoS) provision for small cell traffic. Congestion may happen when small cell traffic and other Ethernet traffic converge at the intermediate switches, as shown in Fig. 1. Such congestion results in delay and/or packet loss which are destructive for small cells, because a number of critical cellular operations rely on stringent timing and accurate control information, such as handover and paging. As such, QoS must be configured in the architectures of small cells over Ethernet to protect small cell traffic. Such protection can be implemented with IEEE 802.1Q standard [4] that defines Virtual Local Area Networks (VLANs) in Ethernet. In particular, small cell traffic can be isolated from other Ethernet traffic by VLAN tagging, which contains Priority Code Point (PCP) in the Ethernet frame header. PCP specifies a priority value from 0 (lowest) to 7 (highest), representing traffic types of Background, Best Effort, Excellent Effort, Critical Application, Video, Voice, Internet Control, and Network Control. These levels are used by Ethernet switches to differentiate traffic and provide QoS to control traffic and critical applications. As per small cells over Ethernet, synchronization messages can be designated as Internet Control Priority (PCP = 6), and small cell backhaul traffic can be designated as Critical Applications (PCP = 3), while Ethernet data traffic and any other untagged traffic stay as Best Effort (PCP = 0).

Another key challenge of small cells over Ethernet is to synchronize the small cells, which is critical to handover and other multi-cell operations. IEEE 802.3 standard specifies Ethernet clocks to be within \( \pm 100 \) ppm [5], which cannot meet the stringent requirement of less than \( \pm 0.1 \) ppm for LTE small cells [6]. In the absence of accurate frequency references (e.g., GPS) in indoor environments, small cells can be synchronized using network synchronization protocols, such as the state-of-the-art IEEE 1588v2 Precision Time Protocol (PTP) [3]. PTP operates in two stages. In the first stage, PTP establishes a master-slave hierarchy of clocks, where the SCBSs are slaves to the switches they are connected to, and the switches are slaves to other switches that are closer to a grandmaster clock acting as the primary clock reference. (In Fig. 1, the grandmaster clock can be the root switch that is the closest to the router/gateway). In the next stage, PTP can synchronize the slave clocks with their master clocks in a peer-to-peer mode by exchanging time reference messages and calculating one-way delays. Ultimately, all clocks are synchronized to the grandmaster clock. PTP can also synchronize all clocks with the grandmaster clocks in an end-to-end mode. In that case, time reference messages are exchanged between the grandmaster clock and every slave clock, and the end-to-end delays are calculated. In Ethernet, PTP is able to synchronize...
distributed small cells’ clocks with a time accuracy of less than 1 microsecond [7]. To meet the frequency accuracy of ±0.1 ppm for LTE small cells, the SCBSs can count and adjust the numbers of their oscillators’ cycles for ten seconds before their frequencies are synchronized.

However, being a packet-based solution, PTP is susceptible to packet-based impairments such as packet delay variation [3]. For this reason, there is growing interest in deploying PTP together with synchronous Ethernet (SyncE) [3, 5]. SyncE is the state-of-the-art physical layer technology/interface that delivers frequency references in Ethernet. To be specific, it derives frequency from the received bit stream and passes that information up to the system clock. The system clock in a switch or a router is an actual oscillator whose output is used as the clock source for all the outputs from the device. With SyncE interfaces, the frequency accuracy can be improved from the original ±100 ppm to ±4.6 ppm in a “free-run” state, where synchronization with the primary clock reference is lost. In this article, analysis on the tolerance of small cells to such a “free-run” state will be provided, which is of practical interest to deploy small cells over Ethernet.

III. COOPERATIVE SMALL CELLS OVER ETHERNET

In many indoor scenarios, small cells need to operate at the same frequency in a cooperative way due to strong inter-cell interference and the scarcity of frequency resources [8]. Generally, there are two approaches to implementing cooperative small cells over Ethernet: centralized and distributed.

A. Centralized Cooperative Small Cells over Ethernet

Consider a scenario where a number of LTE users are served by a group of cooperative small cells that have overlapping coverage. Each user is associated with one of the cells, i.e., synchronized to the SCBS. When multiple users send data at the same time, all the SCBSs around the users receive. In existing approaches, the SCBSs carry out Fast Fourier Transform (FFT) to convert their received orthogonal frequency-division multiplexing (OFDM) signals to a number of parallel subcarriers, and quantize and backhaul the In-phase/Quadrature (I/Q) signals on the subcarriers to a central entity (e.g., the SCNC) where the signals are jointly detected to suppress interference, exploiting multiple-input multiple-output techniques [8]. Such an approach is referred to as Centralized Signal Combining (CSC).

However, when deployed with Ethernet backhaul, CSC would lead to a critical challenge of a significantly increased backhaul bandwidth requirement, especially for small cell uplink. The reason is that CSC requires the SCBSs to send their received and quantized I/Q signals to the SCNC [8]. The quantization would lead to a multi-fold increase in Ethernet backhaul traffic, compared to the actual user data. Take example of 3GPP LTE with 10 MHz bandwidth and 1024 OFDM subcarriers, where the symbol length is 66.7 microseconds and 600 OFDM subcarriers carry data [6]. In uplink, every SCBS transforms its received OFDM signal to 1024 subcarriers, and quantizes the 600 data-carrying subcarriers. If the SCBS sends 4-bit quantized I/Q signals of the 600 subcarriers with a code rate of $\frac{4}{5}$, the backhaul traffic is $600 \times 4 \times 2 \times \frac{66.7}{2} = 144$ Mbit/s per cell. Only six small cells can be supported in a Gigabit Ethernet. The backhaul traffic growth for the downlink of cooperative small cells is more tractable, where the SCNC can multicast original data to the cooperative SCBSs, and the SCBSs independently precode and cooperatively transmit the data. As such, downlink backhaul traffic only increases in the vicinity of the users.

Such an increased backhaul bandwidth requirement would degrade the synchronization accuracy of small cells, especially in the presence of a large amount of Ethernet data traffic. If backhaul traffic and synchronization messages are treated equally without QoS protection, a large amount of Ethernet data traffic and backhaul traffic may result in congestion. The synchronization messages get delayed or even lost. The SCBSs would operate in a “free-run” state, where a frequency error of ±4.6 ppm can be undergone [3]. This is detrimental to CSC, because each user is synchronized with one SCBS. Frequency offsets between the SCBS and other SCBSs would increase the SCBS’s quantization errors of the I/Q signals of the users synchronized with other SCBSs.

B. Distributed Cooperative Small Cells over Ethernet

In order to address the challenge of substantial backhaul traffic growth of CSC, we propose a new distributed approach, called Distributed Switching and Combining (DSC), which can be implemented for the uplink of cooperative small cells.

In DSC, each cooperative SCBS independently demodulates wireless signals into bitwise soft information [i.e., log-likelihood ratio (LLR) of every binary bit] using its own measured wireless channels. The SCBS can also decode the actual user data behind the soft information, and assess whether decoding is successful by cyclic redundancy check (CRC). If successful, the SCBS sends the user data destined for the SCNC; otherwise, the SCBS quantizes and sends the soft information destined for the SCNC.

Such distributed signal processing is tolerant to the large frequency errors in the “free-run” state, as mentioned in Section III-A. This is because DSC does not quantize I/Q signals (as opposed to CSC, as described in Section III-A) and therefore is free of the quantization errors that would grow with the frequency offset.

On the Ethernet backhaul of DSC, soft information of the same user data or the user data itself (if successfully decoded at a SCBS), capsuled in Ethernet frames, is sent from the cooperative SCBSs to the SCNC. These frames gather at Ethernet switches, where they are combined in a distributed manner. To be specific, in the case where there is successfully decoded user data at a switch, the data will be passed towards the SCNC. The soft information of the user data from other SCBSs will be discarded or rejected. In the other case where there is no successfully decoded user data at the switch, the soft information of the same user data from multiple SCBSs will be combined by bitwise adding up. It is possible to decode the combined soft information. If decoding is successful, the decoded user data will be forwarded towards the SCNC; otherwise, the combined soft information will be forwarded.
Such distributed combining ensures that the backhaul traffic does not accumulate on its way to the router/gateway, since only a single (combined) version of soft information representing each user’s data or the user data itself is output at every switch. This addresses the issue of significantly increased backhaul bandwidth requirement described in Section III-A. In fact, the backhaul traffic decreases along its backhaul path with more switches it goes through, because an increasing number of combining operations will improve the likelihood of user data being successfully decoded.

A new stand-alone plug-and-play device, called Small Cell Soft Combiner (SCSC), can be developed to implement DSC at the switches. The structure of the SCSC is illustrated in Fig. 2, where colour coded blocks represent the Ethernet frames that contain the soft information or successfully decoded data of four different users. Two examples of the SCSC output are provided. In Example 1, the combined soft information in blue and white blocks can be successfully decoded. The numbers of these blocks are reduced from four to two each, since the decoded actual user data is to be output. In contrast, the combined soft information in orange and green blocks cannot be decoded, and the numbers of those blocks stay unchanged. In Example 2, the attempt to decode the combined soft information in any block fails. The combined soft information is the output of the SCSC, and the numbers of blocks stay unchanged. The SCSC can be connected to a switch port, as part of the VLAN described in Section II. It does not require stringent synchronization, as what it does is to understand what user data the soft information corresponds to and add up the soft information corresponding to the same data.

A new Ethernet protocol can also be run between the SCSC and the SCBCs connected to the same switch to reduce the backhaul traffic switched at the switch. In the protocol, each of the SCBSs (and the SCSCs attached to the immediate child switches) sends a message to indicate the content type of their Ethernet frames, actual user data or soft information, before sending the frames to the SCSC. Each time receiving a message indicating actual user data, the SCSC rejects other SCBSs sending Ethernet frames by broadcasting a message to those SCBSs, thereby avoiding wasting Ethernet bandwidths.

A similar idea of intermediate decision points is traditionally adopted in distributed detection problems [9]. That idea can be applied in our small cell architecture to analyse the important issue of network topology. We note, though, that the distributed detection mechanisms presented in [9] are not directly applicable to small cell traffic. The reason is that the complexity of the traditional methods becomes prohibitive at the intermediate points (i.e., the SCSCs) when high data rate small cell traffic is considered. As a result, we reach different conclusions from [9].

Our first observation is that for a given number of cooperative small cells, the small cell throughput of DSC is independent of the backhaul topology. In the case of star topologies, soft information of all the SCBSs is forwarded to the root switch and combined (i.e., added up). In the case of serial/chain and tree topologies, soft information of the SCBSs is added up each time gathering at an intermediate switch, and forwarded to the next switch along the backhaul topology. No decision is made at the intermediate point, unless the decision can be verified correct by CRC and therefore is the same as the one that would be made at the root switch. In both of the cases, soft information of all the SCBSs is added up at the root switch and decoded for a hard decision. As a result, the small cell throughput is unaffected by the network topologies. This is different from the traditional distributed signal detection methods for sensor networks, where every sensor makes a local decision based on its own observation and the decisions of upstream sensors along the topology of the sensor network. Such a local decision heavily relies on the topology and the depth of the sensor network, and so does the final global decision of the whole network.

On the other hand, Ethernet backhaul traffic is affected by the network topology in DSC. For example, in a serial/chain or tree topology the output backhaul traffic of the switches does not grow along the switch chain; while in a star topology, the soft information of all the SCBSs aggregates at the root switch which would be heavily loaded. Root switches are often the bottlenecks of Ethernet. In this sense, serial/chain or tree is a preferable topology to practically implement DSC, alleviating heavily loaded root switches.

C. Comparison with CPRI

CPRI defines a publicly available specification for the key interface between a Radio Equipment Control (REC) and a Radio Equipment (RE) [10]. It specifies digitized I/Q signals, as well as Ethernet as one of the transmission protocols, on the interface.

The general architecture of cooperative small cells with Ethernet is different from CPRI. The architecture of cooperative small cells over Ethernet is backhaul which connects SCBSs to the gateway. It does not split a base station. In contrast, CPRI is fronthaul, which physically splits a base station and connects different parts of a single base station. Of course, a SCBS can be more expensive than a RE in terms of cost.
and complexity, while SCBSs are much powerful in terms of functionality and capability.

In terms of the fronthaul/backhaul signals on the Ethernet interface, the centralized and distributed architectures of cooperative small cells over Ethernet - CSC and DSC, are also different from CPRI, especially when OFDM techniques are employed. For CSC, the SCBSs can pre-process OFDM signals to a number of subcarriers, and quantize and send the I/Q components of the subcarriers that carry data on the interface. For DSC, the SCBSs transmit demodulated/decoded signals on the Ethernet interface. In contrast, the REs of CPRI quantize the I/Q components of the received OFDM signals. As a result, the Ethernet fronthaul traffic of CPRI is higher than the Ethernet backhaul traffic that the cooperative small cells generate. Taking the LTE example discussed in Section III-A, every RE would produce \((1 + 16.7/66.7) \times 1024 \times 4 \times 2 \times 2/66.7 \approx 307.14\) Mbit/s, where 16.7 is a standard cyclic prefix length in microseconds. This is much higher than 144 Mbit/s in CSC.

It is worth pointing out that both CSC and CPRI process signals in a centralized manner. The throughput of cooperative small cells using CSC is therefore equal to that of a set of distributed REs with the same fronthaul/backhaul topology. In this sense, the throughput results of CSC in Section IV can be used to present CPRI.

**IV. PRACTICAL CASE STUDY**

In this section, MATLAB and ns-2 simulations are carried out to quantitatively evaluate cooperative small cells over Ethernet, where two Ethernet topologies (with respect to the switches) are considered. One is a chain, as illustrated in Fig. 1; the other is a star, where the switches in the figure are connected as such that Switches 1 to 4 are directly connected to Switch 5. The 3GPP LTE system described in Section III-A is considered.

Without loss of generality, our evaluation is based on one OFDM subcarrier and three active user terminals. The energy per bit to noise power spectral density ratio is 25 dB. 16 quadrature amplitude modulation (QAM) and \(\frac{1}{2}\)-rate convolutional coding are employed. The uncoded small cell packet length is 96 bits. An independent and identically distributed wireless Rayleigh fading channel is assumed for the small cells, as it is typical in rich multipath indoor environments. Ethernet transmission on every single-hop Ethernet link is assumed to be error-free. (This is not an assumption of a lossless Ethernet, as Ethernet frames may be dropped due to buffer overflow.) This assumption is realistic. One reason is that the frequency error at the SCBSs is up to several parts per million, referring to [6]. Such a frequency error can be detrimental to radio links of small cells. However, it is negligible to the Ethernet synchronization requirement of ±100 ppm specified by IEEE 802.3 standard [2], and would not cause transmission errors in Ethernet. Another reason is that the bit error rate is negligible on wired links, compared to wireless links. One more reason lies in an Automatic Repeat reQuest (ARQ) protocol in Ethernet, which keeps transmitting a frame until it is successfully received and an acknowledgement is returned [2].

In the simulations, the quantization levels are optimally designed to allow each level to be equally likely accessed for both of the distributed and centralized cooperative small cells over Ethernet approaches - DSC and CSC. For DSC, the levels are based on the distribution of LLRs. For CSC, the levels are based on the distributions of Rayleigh channel fading and the constellation of transmit signals.

Fig. 3 evaluates DSC and CSC in terms of overall throughput of the cooperative small cells with the growth of quantization bits \(B\). Frequency accuracies of ±0.05 ppm and ±5.0 ppm are considered. The accuracy of ±0.05 ppm corresponds to an ideal case where the Ethernet is lightly loaded and the SCBSs can be precisely synchronized exploiting PTP. The accuracy of ±5.0 ppm corresponds to a practical heavily loaded Ethernet, where the synchronization messages of the small cells are delayed or lost due to a burst of other Ethernet data traffic, and the SCBSs operate in a “free-run” state.

It is shown that, for both of the two frequency accuracies, DSC is able to significantly surpass CSC when \(B\) ≤ 3. This is because a small number of quantization bits is sufficient to represent the soft information (generated with precise channel information), which is important to successful combining and decoding of DSC. In contrast, a small number of quantization bits is insufficient to characterize wireless channels and I/Q signals. As a result, CSC undergoes a severe packet loss, and its throughput is low. It is also shown that DSC and CSC converge with the increasing number of quantization bits. Note that CSC combines signals in a globally optimal way, and therefore can achieve the best throughput when wireless channels and I/Q signals are precisely quantized (\(B\) is large). In this sense, DSC can approach the best throughput, when \(B\)
is increased.

It is confirmed that the throughput of DSC is unaffected by the Ethernet backhaul topology. Specifically, for both of the frequency accuracies of ±0.05 and ±5.0 ppm, the chain and star topologies can achieve the same throughput. It is also confirmed that DSC is more tolerant to frequency errors than CSC, especially when the number of quantization bits is small. This is because the throughput gap between the two approaches is much larger under the frequency accuracy of ±5.0 ppm than it is under ±0.05 ppm.

Fig. 4 compares the backhaul traffic of DSC and CSC, corresponding to the frequency accuracy of ±5.0 ppm in Fig. 3. Here, the backhaul traffic is defined to be the traffic switched at the root switch for small cell backhaul. For DSC, the input from the SCSC attached to the root switch has also been taken into account, apart from the backhaul input from the child switches and the SCBS connected to the root switch. For CSC, the backhaul traffic switched at the root switch contains the output of all the SCBSs, and it does not change with backhaul topologies. This comparison is of practical interest, as a root switch is often the bottleneck of Ethernet.

It is observed that the backhaul topology is critical to the backhaul traffic of DSC at the root switch. A star topology generates substantially more backhaul traffic at the root switch than a chain topology. Fortunately, the backhaul traffic of the star topology can be significantly reduced by converting it to a tree. We can add two switches (and two SCSCs) into the Ethernet. One connects Switches 1 and 2 to Switch 5, and the other connects Switches 3 and 4 to Switch 5, resulting in a binary tree. As a result, the backhaul traffic drops by 73%.

It is noted that in the chain topology the lowest backhaul traffic of DSC is observed when \( B = 3 \). This is the case where the best trade-off can be achieved between the backhaul traffic reduction contributed by an improved quantization accuracy (and subsequently increased actual user data in the chain) and the backhaul traffic growth caused by increased quantization bits. Further increasing \( B \) contributes marginally to increasing successful user data and reducing quantized soft information in the chain, as implied in Fig. 3.

Considering the same small cell throughput that DSC requires \( B = 3 \) to achieve in a chain topology, whereas CSC requires \( B = 5 \) (as shown in Fig. 3). Fig. 4 confirms that DSC only requires 36% as much backhaul traffic as CSC does to achieve the same throughput. As a result, DSC can support three times the cooperative small cells of CSC.

Fig. 5 evaluates the tolerance of DSC and CSC to frequency errors, where the chain topology is considered and the frequency accuracy decreases from 0 to ±5.0 ppm. It shows that DSC is substantially more tolerant to frequency errors, especially in a “free-run” state with a large frequency error of over ±4.6 ppm. Particularly, for \( B = 4 \), DSC does not degrade until the frequency error is larger than ±2.5 ppm, whereas CSC starts to degrade once the frequency error exceeds ±1.0 ppm. This is because CSC quantizes channel coefficients based on a priori channel distribution. Large frequency errors would lead to a discrepancy between the actual and the a priori channel distributions, resulting in channel quantization errors. In contrast, DSC exploits accurate channel coefficients at each small cell to process signals in a distributed manner. It does not experience channel quantization errors.

The figure also reveals that the frequency error tolerance of DSC is robust to backhaul traffic reduction (resulting from decreasing \( B \)). Particularly, in the case where a smaller number of quantization bits is used (\( B = 3 \)), the throughput loss of DSC is less than 6.4%, compared to the case of \( B = 4 \). In contrast, the loss of CSC is substantial, up to 42.9%.

Finally, Fig. 6 shows the impact of small cell backhaul traffic on Ethernet data traffic in a practical Gigabit Ether-
Data loss probability of Ethernet data traffic versus Ethernet data traffic demand, where the small cell backhaul traffic is given priority.

net network that is shared between small cell backhaul and Ethernet data traffic. $B = 4$ for both CSC and DSC. The chain topology is considered. Given 600 data subcarriers of the LTE small cell system, the small cells using CSC generate the backhaul traffic of 360 Mbits/s ($600 \times 600 \text{ kbits/s}$) at the router/gateway, referring to Fig. 3. Using DSC, the small cells generate the backhaul traffic of only 52.65 Mbits/s ($87.75 \times 600 \text{ kbits/s}$) at the router/gateway. Configuring Ethernet QoS as described in Section II, we can see that CSC has a significant impact on data traffic with a large amount of data loss. On the other hand, DSC is much less intrusive, such that the network can accommodate 50% more data traffic than it can when CSC is used.

V. CONCLUSIONS

We introduced a new distributed scheme, DSC, to address the challenges of significantly increased backhaul traffic and frequency errors in cooperative small cells with Ethernet backhaul. The scheme requires less backhaul traffic, tolerates large frequency errors, distributes computational complexities, and can be easily scaled up in chain and tree topologies for coverage extension. Our case study shows that DSC can reduce up to 64% of the small cell backhaul traffic, and is tolerant to a large frequency error of $\pm 5.0$ ppm in a “free-run” state. Given such a low backhaul traffic requirement, the scheme can support three times as many cooperative small cells as the conventional centralized approach.

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