Small Cell Dynamic TDD Transmissions in Heterogeneous Networks

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Abstract—**Future wireless communication systems feature heterogeneous networks (HetNets), with small cells underlying existing macrocells. In order to maximize the off-loading benefits of small cells and mitigate the interference from the macrocell tier to the small cell tier, cell range expansion (CRE) and almost blank subframes (ABSs) have been designed for small cells and macrocells, respectively. Besides, enhanced 4th generation (4G) networks are also envisaged to adopt dynamic time division duplexing (TDD) transmissions for small cells to adapt their communication service to the fast variation of downlink (DL) and uplink (UL) traffic demands. However, up to now, it is still unclear whether it is technically feasible to introduce dynamic TDD into HetNets. In this paper, we investigate this fundamental problem and propose a feasible scheme to enable small cell dynamic TDD transmissions in HetNets. Simulation results show that compared with the static TDD scheme with CRE and ABS operations, the proposed scheme can achieve superior performance gains in terms of DL and UL packet throughputs when the traffic load is low to medium, at the expense of introducing the DL-to-UL interference cancellation (IC) functionality in macrocell base stations (BSs) and/or small cell BSs.**

I. INTRODUCTION

Future wireless communication networks feature advanced architectures and topologies, typically referred to as heterogeneous networks (HetNets), with small cells underlying existing macrocells [1]. In a HetNet scenario, small cells such as metrocells, picocells, femtocells and relay nodes overlay conventional macrocells, bringing the radio access network (RAN) closer to user equipment (UE) and increasing network performance by means of traffic off-loading and cell splitting.

The Third Generation Partnership Project (3GPP) Long Term Evolution Advanced (LTE-A) HetNets adopted cell range expansion (CRE) to maximize the benefits of small cells. With CRE, the coverage of a small cell can be artificially increased by instructing UEs to add a positive range expansion bias (REB) in dB scale to the reference signal receiving power (RSRP) of the small cell [2]. However, the better spatial reuse and improved uplink (UL) connection offered by CRE comes at the expense of reduced downlink (DL) signal-to-interference-plus-noise ratios (SINRs) for expanded-region (ER) UEs, since they no longer connect to the base station (BS) providing the strongest level of signal reception.

In order to alleviate this interference problem, LTE-A networks implement time-domain enhanced inter-cell interference coordination (eICIC) by introducing almost blank subframes (ABSs) [3]. In more detail, in the DL, macrocells schedule ABSs that are subframes in which only common reference signals (CRSs) and the most important cell-specific broadcast information are transmitted, and small cells typically schedule their ER UEs in those DL subframes overlapping with the macrocell ABSs. In this way, the devastating interference from macrocell BSs to ER UEs is avoided. In [4], the authors provided an algorithm for calculating REB and proposed a cooperative scheduling scheme to mitigate both DL and UL interference caused by macrocells and macrocell UEs to ER UEs and small cells, respectively. The application of ABSs in more complicated scenarios containing three tiers of BSs was addressed in [5]. Moreover, low power ABSs (LP-ABSs) where macrocells apply a power reduction on macrocell DL subframes instead of blanking were investigated in [6].

It can also be envisaged that in future networks, e.g., the 3GPP LTE Release 12/13 networks, small cells will prioritize time division duplexing (TDD) schemes over frequency division duplexing (FDD) ones since TDD transmissions are particularly suitable for hot spot scenarios with traffic fluctuations in both link directions [7]. In this line, a new technology has recently emerged, referred to as dynamic TDD, in which TDD DL and UL subframes can be dynamically configured in small cells to adapt their communication service to the fast variation of DL/UL traffic demands in either direction. The application of dynamic TDD in homogeneous small cell networks has been investigated in recent works with positive results [8], [9]. Gains in terms of UE packet throughput (UPT) and energy saving have been observed, mostly in low-to-medium traffic load conditions. However, up to now, it is still unclear whether it is feasible to introduce the dynamic TDD transmissions into HetNets because it will complicate the existing CRE and ABS operations and its advantage in the presence of macrocells in terms of UPT has not been confirmed yet in the existing literature [7].

Motivated by the promising technologies of HetNets and dynamic TDD, we investigate the technical feasibility of in-
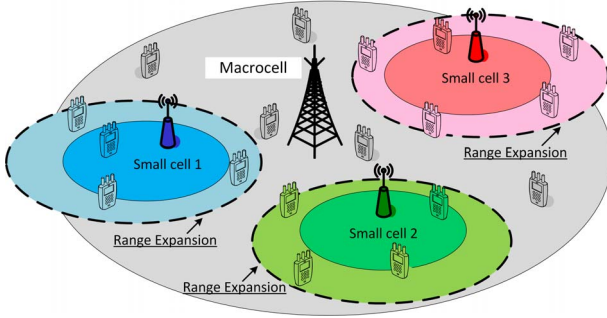
Fig. 1. Illustration of SCE Scenario 1.

troducing dynamic TDD into HetNets, and propose a solution to enable small cell dynamic TDD transmissions in a HetNet scenario with co-channel deployment of macrocells and small cells. In this paper, based on a novel scheduling policy, our contributions are two-fold:

- We propose an algorithm to jointly determine UE cell association and macrocell ABS duty cycles, i.e., the number of subframes in which macrocells should mute data transmissions in every T subframes;
- We propose an algorithm to determine the appropriate DL and UL subframe splitting for dynamic TDD small cells.

The rest of the paper is organized as follows. The considered network scenario is described in Section II. The proposed schemes for small cell dynamic TDD operations in HetNets are presented in Section III. Simulation results and some concluding remarks are provided in Section IV and V, respectively.

II. NETWORK SCENARIO

In this paper, we consider a HetNet scenario with co-channel deployment of macrocells and small cells, which is currently under investigation in the 3GPP framework, and is known as the small cell enhancement (SCE) Scenario 1 [10] as illustrated by Fig. 1.

In Fig. 1, the m-th macrocell BS, the n-th small cell BS, and the k-th UE are denoted as $b(m), m \in \{1, 2, ..., M\}$, $c(n), n \in \{1, 2, ..., N\}$, and $u(k), k \in \{1, 2, ..., K\}$, respectively. In order to determine UE cell association, two measures, RSRP and wide-band (WB) DL SINR, have been widely used in practical systems, e.g., LTE-A networks [11]. The RSRP and WB DL SINR measured at UE $u(k)$ associated with macrocell BS $b(m)$ are denoted as $\mathrm{RSRP}^\mathrm{M}_{m,k}$ and $\gamma^\mathrm{M}_{m,k}$, respectively. The counterpart measures with regard to small cell BS $c(n)$ are denoted as $\mathrm{RSRP}^\mathrm{S}_{n,k}$ and $\gamma^\mathrm{S}_{n,k}$, respectively.

Based on the best RSRP criterion:

- Without CRE in small cells, the set of macrocell UEs served by macrocell BS $b(m)$ is denoted by $U^\mathrm{M}_m = \{u(q^\mathrm{M}_{m,1}), ..., u(q^\mathrm{M}_{m,k}), ..., u(q^\mathrm{M}_{m,K_1(m)})\}$, where $Q^\mathrm{M}_m = \{q^\mathrm{M}_{m,1}, ..., q^\mathrm{M}_{m,k}, ..., q^\mathrm{M}_{m,K_1(m)}\}$ is the set of indices of such macrocell UEs and $K_1(m)$ is its cardinality. The DL traffic arriving rate, UL traffic arriving rate, DL data buffer and UL data buffer of macro-

cell UE $u(q^\mathrm{M}_{m,k})$ are respectively denoted as $\lambda^\mathrm{DL}(q^\mathrm{M}_{m,k})$, $\lambda^\mathrm{UL}(q^\mathrm{M}_{m,k})$, $\omega^\mathrm{DL}(q^\mathrm{M}_{m,k})$ and $\omega^\mathrm{UL}(q^\mathrm{M}_{m,k})$.

- Without CRE in small cells, the set of small cell UEs served by small cell BS $c(n)$ is denoted by $U^\mathrm{S}_n = \{u(q^\mathrm{S}_{n,1}), ..., u(q^\mathrm{S}_{n,k}), ..., u(q^\mathrm{S}_{n,K_2(n)})\}$, where $Q^\mathrm{S}_n = \{q^\mathrm{S}_{n,1}, ..., q^\mathrm{S}_{n,k}, ..., q^\mathrm{S}_{n,K_2(n)}\}$ is the set of indices of original small cell UEs and $K_2(n)$ is its cardinality. The DL traffic arriving rate, UL traffic arriving rate, DL data buffer and UL data buffer of small cell UE $u(q^\mathrm{S}_{n,k})$ are respectively denoted as $\lambda^\mathrm{DL}(q^\mathrm{S}_{n,k})$, $\lambda^\mathrm{UL}(q^\mathrm{S}_{n,k})$, $\omega^\mathrm{DL}(q^\mathrm{S}_{n,k})$ and $\omega^\mathrm{UL}(q^\mathrm{S}_{n,k})$.

- After the CRE operations, some macrocell UEs will migrate to small cells to achieve traffic off-loading from the macrocell tier to the small cell tier. Then, the set of off-loaded macrocell UEs, i.e., ER UEs, to small cell BS $c(n)$ is denoted as $U^\mathrm{M2S}_n = \{u(r^\mathrm{S}_{n,1}), ..., u(r^\mathrm{S}_{n,k}), ..., u(r^\mathrm{S}_{n,K_3(n)})\}$, where $R^\mathrm{M2S}_n = \{r^\mathrm{S}_{n,1}, ..., r^\mathrm{S}_{n,k}, ..., r^\mathrm{S}_{n,K_3(n)}\}$ is the set of indices of such ER UEs and $K_3(n)$ is its cardinality. The DL traffic arriving rate, UL traffic arriving rate, DL data buffer and UL data buffer of ER UE $u(r^\mathrm{S}_{n,k})$ are respectively denoted as $\lambda^\mathrm{DL}(r^\mathrm{S}_{n,k})$, $\lambda^\mathrm{UL}(r^\mathrm{S}_{n,k})$, $\omega^\mathrm{DL}(r^\mathrm{S}_{n,k})$ and $\omega^\mathrm{UL}(r^\mathrm{S}_{n,k})$.

III. PROPOSED DYNAMIC TDD OPERATION

In this paper, we assume that TDD is adopted by both the macrocell and the small cell tiers. In practical networks, the macrocell tier normally employs a uniform and quasi-static configuration of DL/UL subframe splitting and ABS duty cycle because the aggregated macrocell traffic dynamics are usually averaged out due to the fairly large number of macrocell UEs per macrocell site. In addition, with a quasi-static configuration of DL/UL subframe splitting, the detrimental DL-to-UL interference in the macrocell tier can be avoided. However, traffic behaviour is completely different in the small cell tier, mostly because the UEs served by a small cell can be very few, leading to drastic DL/UL traffic fluctuations, which are particularly suitable for dynamic TDD operations. Thereby, in this paper, we propose that the macrocell tier uses a quasi-static configuration of DL/UL subframe splitting, which matches its statistical DL/UL traffic ratio, and consider dynamic TDD only for the small cell tier. Moreover, when considering dynamic TDD transmissions for small cells, it is important to consider the following design aspects:

- scheduling policy in small cells, i.e., what is the behaviour of small cells in macrocell DL, UL and ABS subframes,
- UEs' cell association after the CRE operation,
- macrocells' ABS duty cycle, and
- small cell specific dynamic TDD DL/UL subframe splitting.

In the following subsections, we look at these issues in detail.

A. Scheduling policy in dynamic TDD small cells

It is apparent that any UL transmission attempt intended for small cell BSs will find itself in an extremely adverse situation in the subframes aligned with macrocell DL subframes, since DL signals emitted from macrocell BSs are of high power and thus can easily jam small cell UEs' UL signals. Though macrocell DL to small cell UL interference cancellation (IC) techniques based on full or partial prior information of macrocell DL transmissions may solve this problem, the involved complexity is very high for low-cost small cell BSs and thus it is not desirable to abuse IC here. Therefore, we propose that small cells conduct only DL transmissions in the subframes aligned with macrocell DL subframes. As for the subframes overlapping with macrocell UL and ABS subframes, since the interference suffered by small cell BSs and small cell UEs will probably be low because dominant interfering macrocell UEs are very likely to have been off-loaded to small cells, we thus propose that small cells perform dynamic TDD transmissions when macrocells transmit UL or ABS subframes. We will refer to these subframes as dynamic TDD subframes.

Having decided which subframe type should be scheduled at each time in the small cells, another pertinent question is: Which small cell UE(s) should access each subframe type? A widely adopted assumption in LTE-A DL HetNets is that DL packets of ER UEs should be scheduled with a high priority in subframes overlapping with the macrocell ABSs and that they should not be scheduled in subframes overlapping with the macrocell DL subframes [12]. We extend this idea to the HetNet dynamic TDD scenario and propose that

1) Small cell DL packets of ER UEs, i.e., U_n^{M2S}, should be transmitted in small cell dynamic TDD DL subframes.
2) Small cell DL packets of non-ER UEs, i.e., U_n^{S}, should be transmitted in subframes overlapping with the macrocell DL subframes. If the small cell dynamic TDD DL subframes are not occupied, then the non-ER UEs can also access these subframes.
3) Small cell UL packets of all connected UEs, i.e., $U_n^{\text{S}} \bigcup U_n^{\text{M2S}}$, should be transmitted in small cell dynamic TDD UL subframes.

B. UE cell association and macrocell ABS duty cycle

Given the proposed scheduling policy in small cells, next questions to be answered are: To which small cell should each ER UE go? And what is the appropriate ABS duty cycle of the macrocell tier? In order to answer such questions, we propose a new algorithm to jointly determine UE cell association and macrocell ABS duty cycle that encourages load balancing between the macrocell and the small cell tiers and outsources macrocell UEs that may suffer from low capacity to small cells where they may benefit from higher performance.

Algorithm 1 summarizes the proposed algorithm to jointly determine UE cell association and macrocell ABS duty cycle, where A is the number of ABSs given up by macrocells in every T subframes with $A \in \{0, 1, ..., T-1\}$, $\alpha^{\text{M,DL}}$ and $\alpha^{\text{M,UL}}$ are the ratios of DL-to-total subframes and UL-to-total sub-

frames for macrocells, respectively, with $\alpha^{\text{M,DL}} + \alpha^{\text{M,UL}} = 1$, and round$\{x\}$ is an operator that maps x to its closest integer.

Due to the reduced search space of A, Algorithm 1 performs an exhaustive search on A and its objective is to find the optimal A^{opt} such that the average cell traffic demand density for the macrocell and the small cell tiers is minimized[1].

The average cell traffic demand density can be formally defined as the expected traffic influx over the number of subframes in every T subframes to transmit it. More specifically, the average cell traffic demand density of macrocell $b(m)$ in the DL and the UL can be respectively computed as

$$d_m^{\text{M,DL}} = \frac{\sum_{j=1}^{K_1(m)} \lambda^{\text{DL}}(q_{m,j}^{\text{M}})}{f^{\text{M,DL}}}, \tag{1}$$

and

$$d_m^{\text{M,UL}} = \frac{\sum_{j=1}^{K_1(m)} \lambda^{\text{UL}}(q_{m,j}^{\text{M}})}{f^{\text{M,UL}}}, \tag{2}$$

where the expected traffic influx is computed as the sum of the average DL(UL) data buffers, measured by the DL(UL) traffic arriving rates $\lambda^{\text{DL}}(q_{m,j}^{\text{M}})$ ($\lambda^{\text{UL}}(q_{m,j}^{\text{M}})$), over all UEs connected to macrocell $b(m)$, and $f^{\text{M,DL}}(f^{\text{M,UL}})$ is the number of available DL(UL) subframes in every T subframes. It is important to note that according to our discussions in Section III-A, $f^{\text{M,DL}}$ and $f^{\text{M,UL}}$ take network-wide values for all macrocells because of the static TDD transmissions in the macrocell tier and we have $f^{\text{M,DL}} + f^{\text{M,UL}} + A = T$. The functioning of Algorithm 1 is explained in the following, where for each possible A the following operations are performed.

For each macrocell, we first sort its set of connected UEs U_m^{M} according to their ascending order of SINR $\gamma_{m,k}$, and get the following sorted set $\bar{U}_m^{\text{M}} = \left\{ u(q_{m,\pi(1)}^{\text{M}}), \ldots, u(q_{m,\pi(k)}^{\text{M}}), \ldots, u(q_{m,\pi(K_1(m))}^{\text{M}}) \right\}$. The first UE in the sorted set is the first candidate UE to be off-loaded to a small cell, and candidate UEs are examined sequentially.

For the k-th tested candidate UE $u(q_{(m,\pi(k))}^{\text{M}})$, $d_m^{\text{M,DL}}$ and $d_m^{\text{M,UL}}$ in (1) and (2) should be updated as follows

$$d_m^{\text{M,DL}} = \frac{\sum_{j=1}^{K_1(m)} \lambda^{\text{DL}}(q_{m,j}^{\text{M}}) - \lambda^{\text{DL}}(q_{m,\pi(k)}^{\text{M}})}{f^{\text{M,DL}}}, \tag{3}$$

$$d_m^{\text{M,UL}} = \frac{\sum_{j=1}^{K_1(m)} \lambda^{\text{UL}}(q_{m,j}^{\text{M}}) - \lambda^{\text{UL}}(q_{m,\pi(k)}^{\text{M}})}{f^{\text{M,UL}}}. \tag{4}$$

Then, in order to determine the new serving cell of the tested candidate UE $u(q_{m,\pi(k)}^{\text{M}})$, all small cells are sorted according to the descending order of $RSRP_{n,q_{m,\pi(k)}^{\text{M}}}^{\text{S}}$. The sorted small cell set is UE-specific and denoted as $C(q_{m,\pi(k)}^{\text{M}}) = \{c(\zeta(1)), \ldots, c(\zeta(l)), \ldots, c(\zeta(N))\}$. The first small cell in the sorted set is the first candidate small cell to host the candidate UE, and candidate small cells are examined sequentially.

Because it has been proposed in our scheduling policy that small cell DL packets of non-ER UEs should be typically transmitted in subframes overlapping with the macrocell DL

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[1]In practice, different operators may have different objectives and could select different optimization targets. But there is always a trade-off between the macrocell and small cell UPTs [13], i.e., increasing macrocell UPT reduces small cell UPT and vice versa. Intuitively, A^{opt} tends to be larger if an operator wants to put more emphasis on the performance of the small cell tier.

subframes, for each tested candidate small cell $c(\zeta(l))$, its average DL traffic demand density in subframes aligned with macrocell DL subframes can be calculated as

$$d_{\text{M\_DL\_sf}}^{\text{S,DL}} = \frac{\sum_{j=1}^{K_2(\zeta(l))} \lambda^{\text{DL}}(q_{\zeta(l),j}^{\text{S}})}{f^{\text{M,DL}}}. \tag{5}$$

Having updated the average DL traffic demand density in subframes aligned with macrocell DL subframes, it is important to note that Algorithm 1 also searches for the statistically optimal splitting of dynamic TDD DL/UL subframes for the candidate small cell $c(\zeta(l))$, which is isolated from Algorithm 1 and presented in Algorithm 2 for future use in Section III-C.

In Algorithm 2, we propose that the statistically optimal number of dynamic TDD UL subframes for small cell $c(\zeta(l))$, denoted as $t_{\zeta(l)}^{\text{STAT-opt}}$, should be derived with the objective of minimizing the difference between the average DL and UL traffic demand densities so that a balanced DL/UL UPT performance in such small cell can be achieved. For a candidate number of dynamic TDD UL subframes t and the tested candidate UE $u(q_{(m,\pi(k))}^{\text{M}})$, based on our proposed scheduling policy, in which ER UE DL traffic and all UE UL traffic should be served by dynamic TDD transmissions in subframes colliding with macrocell UL and ABS subframes, the average DL and UL traffic demand density in dynamic TDD subframes for the candidate small cell $c(\zeta(l))$ can be respectively calculated as

$$d_{\text{dynTDD\_sf}}^{\text{S,DL}}(t) = \frac{\sum_{j=1}^{K_3(\zeta(l))} \lambda^{\text{DL}}(r_{\zeta(l),j}^{\text{S}}) + \lambda^{\text{DL}}(q_{(m,\pi(k))}^{\text{M}})}{f^{\text{S,dynTDD}} - t}, \tag{6}$$

and

$$d_{\text{dynTDD\_sf}}^{\text{S,UL}}(t) = \frac{1}{t}\left[\sum_{j=1}^{K_2(\zeta(l))} \lambda^{\text{UL}}(q_{\zeta(l),j}^{\text{S}}) + \sum_{j=1}^{K_3(\zeta(l))} \lambda^{\text{UL}}(r_{\zeta(l),j}^{\text{S}}) + \lambda^{\text{UL}}(q_{(m,\pi(k))}^{\text{M}})\right], \tag{7}$$

where $f^{\text{S,dynTDD}}$ is the number of small cell dynamic TDD subframes in every T subframes and we have $f^{\text{S,dynTDD}} = f^{\text{M,UL}} + A$. Then, $t_{\zeta(l)}^{\text{STAT-opt}}$ can be derived as

$$t_{\zeta(l)}^{\text{STAT-opt}} = \arg\min_{t}\left\{\left|d_{\text{dynTDD\_sf}}^{\text{S,UL}}(t) - d_{\text{dynTDD\_sf}}^{\text{S,DL}}(t)\right|\right\}. \tag{8}$$

Having obtained $t_{\zeta(l)}^{\text{STAT-opt}}$, the average UL traffic demand density in small cell $c(\zeta(l))$ can be calculated as

$$d_{\zeta(l)}^{\text{S,UL}} = d_{\text{dynTDD\_sf}}^{\text{S,UL}}(t_{\zeta(l)}^{\text{STAT-opt}}). \tag{9}$$

Moreover, we propose that the average DL traffic demand density for the candidate small cell $c(\zeta(l))$ should be the larger one of the average DL traffic demand densities respectively associated with ER UEs and non-ER UEs, which is

$$d_{\zeta(l)}^{\text{S,DL}} = \max\left\{d_{\text{dynTDD\_sf}}^{\text{S,DL}}(t_{\zeta(l)}^{\text{STAT-opt}}), d_{\text{M\_DL\_sf}}^{\text{S,DL}}\right\}. \tag{10}$$

As for a successful off-loading operation, we propose that the average traffic demand density of the candidate small cell should not be larger than that of the source macrocell to avoid small cells taking upon too much burden and becoming new traffic bottlenecks, which is a necessary condition in the load balanced state and it is mathematically formulated as $d_{\zeta(l)}^{\text{S,DL}} < d_m^{\text{M,DL}}$ and $d_{\zeta(l)}^{\text{S,UL}} < d_m^{\text{M,UL}}$. Moreover, we also require that the

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Algorithm 1 Joint selection of UE cell association and macrocell ABS duty cycle

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for $A = 0 : T - 1$ **do**
  Compute $f^{\text{M,DL}} = \text{round}\left\{(T - A) \times \alpha^{\text{M,DL}}\right\}$, $f^{\text{M,UL}} = T - A - f^{\text{M,DL}}$, and $f^{\text{S,dynTDD}} = f^{\text{M,UL}} + A$.
  for $m = 1 : M$ **do**
    Obtain $\bar{U}_m^{\text{M}}$ by sorting $u(q_{m,k}^{\text{M}})$ according to the ascending order of $\gamma_{m,k}^{\text{M}}$.
    for $k = 1 : K_1(m)$ **do**
      Regarding the candidate ER UE $u(q_{m,\pi(k)}^{\text{M}})$, calculate $d_m^{\text{M,DL}}$ and $d_m^{\text{M,UL}}$ using (3) and (4), respectively. Obtain $C(q_{m,\pi(k)}^{\text{M}})$ by sorting all small cells according to the descending order of $RSRP_{n,q_{m,\pi(k)}^{\text{M}}}^{\text{S}}$.
      for $l = 1 : N$ **do**
        Compute $d_{\text{M\_DL\_sf}}^{\text{S,DL}}$ using (5).
        Obtain $t_{\zeta(l)}^{\text{STAT-opt}}$, $d_{\text{dynTDD\_sf}}^{\text{S,DL}}\left(t_{\zeta(l)}^{\text{STAT-opt}}\right)$ and $d_{\text{dynTDD\_sf}}^{\text{S,UL}}\left(t_{\zeta(l)}^{\text{STAT-opt}}\right)$ for the candidate outsourcing small cell $c(\zeta(l))$ using Algorithm 2.
        Update $d_{\zeta(l)}^{\text{S,UL}}$ and $d_{\zeta(l)}^{\text{S,DL}}$ using (9) and (10).
        if $d_{\zeta(l)}^{\text{S,DL}} < d_m^{\text{M,DL}}$ **and** $d_{\zeta(l)}^{\text{S,UL}} < d_m^{\text{M,UL}}$ **and** $RSRP_{m,q_{m,\pi(k)}^{\text{M}}}^{\text{M}} - RSRP_{\zeta(l),q_{m,\pi(k)}^{\text{M}}}^{\text{S}} < y$ **then**
          UE $u(q_{m,\pi(k)}^{\text{M}})$ is outsourced to $c(\zeta(l))$.
          Update the UE cell association as
          $K_3(\zeta(l)) = K_3(\zeta(l)) + 1$;
          $R_{\zeta(l)}^{\text{M2S}} = R_{\zeta(l)}^{\text{M2S}} + \left\{u(q_{m,\pi(k)}^{\text{M}})\right\}$;
          $K_1(m) = K_1(m) - 1$;
          $U_m^{\text{M}} = U_m^{\text{M}} - \left\{u(q_{m,\pi(k)}^{\text{M}})\right\}$.
          Record the average traffic demand density of macrocell $b(m)$ as $d_m^{\text{M}}(A) = \frac{d_m^{\text{M,DL}} + d_m^{\text{M,UL}}}{2}$.
          Obtain the average traffic demand density for small cell $c(\zeta(l))$ as $d_{\zeta(l)}^{\text{S}}(A) = \frac{d_{\zeta(l)}^{\text{S,DL}} + d_{\zeta(l)}^{\text{S,UL}}}{2}$.
          break;
        end if {judgement of a successful outsourcing}
      end for {loop of candidate small cells}
    end for {loop of candidate ER UEs}
  end for {loop of macrocells}
end for {loop of candidate macrocell ABS duty cycles}
Choose the appropriate macrocell ABS duty cycle with the minimum average traffic demand density for both the macrocell and the small cell tiers as $A^{\text{opt}} = \arg\min_{A}\left\{\frac{1}{M+N}\left[\sum_{m=1}^{M} d_m^{\text{M}}(A) + \sum_{n=1}^{N} d_n^{\text{S}}(A)\right]\right\}$. And UE cell association is eventually determined based on A^{opt}.

Algorithm 2 Selection of $t_{\zeta(l)}^{\text{STAT-opt}}$

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for $t = 1 : f^{\text{S,dynTDD}} - 1$ **do**
  Compute $d_{\text{dynTDD\_sf}}^{\text{S,DL}}(t)$ and $d_{\text{dynTDD\_sf}}^{\text{S,UL}}(t)$ using (6) and (7), respectively.
end for
Select $t_{\zeta(l)}^{\text{STAT-opt}}$ using (8).

Algorithm 3 Selection of the optimal number $t_n^{\text{INST-opt}}$ of small cell dynamic TDD UL subframes

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From Algorithm 1, we can obtain $f^{\text{S,dynTDD}} = f^{\text{M,UL}} + A^{\text{opt}}$.

for $n = 1 : N$ **do**

  if $(\exists \omega^{\text{UL}}(q_{n,k}^{\text{S}}) \neq 0, q_{n,k}^{\text{S}} \in Q_n^{\text{S}} \textbf{ or } \exists \omega^{\text{UL}}(r_{n,k}^{\text{S}}) \neq 0, r_{n,k}^{\text{S}} \in R_n^{\text{M2S}})$ **and** $\forall \omega^{\text{DL}}(r_{n,k}^{\text{S}}) = 0, r_{n,k}^{\text{S}} \in R_n^{\text{M2S}}$ **then**

    $t_n^{\text{INST-opt}} = f^{\text{S,dynTDD}}$.

  else if $\forall \omega^{\text{UL}}(q_{n,k}^{\text{S}}) = 0, q_{n,k}^{\text{S}} \in Q_n^{\text{S}}$ **and** $\forall \omega^{\text{UL}}(r_{n,k}^{\text{S}}) = 0, r_{n,k}^{\text{S}} \in R_n^{\text{M2S}}$ **and** $\exists \omega^{\text{DL}}(r_{n,k}^{\text{S}}) \neq 0, r_{n,k}^{\text{S}} \in R_n^{\text{M2S}}$ **then**

    $t_n^{\text{INST-opt}} = 1$.

  else if $\forall \omega^{\text{UL}}(q_{n,k}^{\text{S}}) = 0, q_{n,k}^{\text{S}} \in Q_n^{\text{S}}$ **and** $\forall \omega^{\text{UL}}(r_{n,k}^{\text{S}}) = 0, r_{n,k}^{\text{S}} \in R_n^{\text{M2S}}$ **and** $\forall \omega^{\text{DL}}(r_{n,k}^{\text{S}}) = 0, r_{n,k}^{\text{S}} \in R_n^{\text{M2S}}$ **then**

    $t_n^{\text{INST-opt}} = t_n^{\text{STAT-opt}}$, which has been previously obtained from Algorithm 2 based on A^{opt}.

  else

    Invoke Algorithm 2 to compute $t_n^{\text{INST-opt}}$, with λ and $t_{\zeta(l)}^{\text{STAT-opt}}$ replaced with ω and $t_n^{\text{INST-opt}}$, respectively.

  end if

end for

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link quality between the candidate ER UE and the candidate small cell should be good enough after the CRE operation, i.e., $RSRP_{m,q_{m,k}^{\text{M}}}^{\text{M}} - RSRP_{\zeta(l),q_{m,k}^{\text{M}}}^{\text{S}} < y$, where y is the REB parameter in dB scale for the CRE operation. As a result of these constraints, in our proposed scheme, small cells may reject requests of traffic off-loading from macrocells.

Finally, we select the macrocell ABS duty cycle A^{opt} with the minimum average traffic demand density for the macrocell and the small cell tiers, and then determine UE cell association results, R_n^{M2S} and U_m^{M}, according to the selected A^{opt}.

C. Small cell dynamic TDD DL/UL subframe splitting

Following the design of Algorithm 2, we also propose an algorithm that splits the dynamic TDD DL/UL subframes for each small cell in a more dynamic manner taking instantaneous traffic densities into account. This new algorithm is performed every T subframes and is based on the criterion of minimizing the difference between the instantaneous DL and UL traffic demand densities. Considering the example discussed in Section III-B, the instantaneous DL and UL traffic demand density of $c(n)$ can be defined in a similar way as in (6) and (7) with λ replaced with ω. In Algorithm 3, the proposed algorithm to split the dynamic TDD DL/UL subframes for each small cell is summarized.

Unlike the DL/UL traffic arriving rate in Algorithm 2, the DL/UL data buffer in Algorithm 3 can be zero. Therefore, $t_n^{\text{INST-opt}}$ can be as large as $f^{\text{S,dynTDD}}$ when the corresponding instantaneous DL traffic demand density equals zero. However, in order to keep the UL feedback channel always open for the TDD system to function properly, we recommend that the minimum value of $t_n^{\text{INST-opt}}$ should be set to one, even if there is no instantaneous UL traffic demand. Moreover, when a small cell is completely idle with neither DL nor UL traffic demand, we propose that $t_n^{\text{INST-opt}}$ should be set to $t_n^{\text{STAT-opt}}$ so that the DL/UL subframe splitting in the small cell matches its statistical traffic pattern. For other cases in Algorithm 3, we will invoke Algorithm 2 to obtain $t_n^{\text{INST-opt}}$ with λ^{DL} and λ^{UL} replaced with UE's data buffer ω^{DL} and ω^{UL}, respectively.

TABLE I
KEY SIMULATION PARAMETERS

Parameters	Assumptions
Scenario	HetNet with co-channel deployment
Network layout	7 cell sites, 3 macrocells per cell site, wrap-around
Inter-site distance	500 m
# small cells per macrocell	4 (84 small cells in total)
Small cell deployment	Random deployment, 40 m radius of coverage
# UEs per macrocell	10 UEs uniformly dropped in each macrocell
# UEs per small cell	5 UEs uniformly dropped in each small cell
System bandwidth	10 MHz
# macro/small cell antenna	4 (for both transmission and reception)
# UE antenna	2 (for both transmission and reception)
Codebook for PMI feedback	LTE Release 11 codebook with WB rank adaptation
UE scheduling in each cell	Proportional fairness (PF)
Packet scheduling for UE	Round Robin (RR)
Modulation & coding schemes	QPSK, 16QAM, 64QAM [11] plus 256QAM
Link adaptation	Target BLER being 0.1 for both the DL and the UL
Control ch. and RS overhead	3 out of 14 OFDM symbols per subframe
HARQ modelling	Retransmission in the first available subframe
Small-scale fading channel	Explicitly modelled (EPA channel [14])
Receiver type	MMSE receiver for both the DL and the UL

IV. SIMULATIONS AND DISCUSSIONS

In this section, we present numerical results to evaluate the performance of the proposed schemes. In our simulations, we construct the network layout according to the 3GPP SCE Scenario 1, as illustrated in Fig. 1. The full list of system parameters and the traffic modeling methodology can be found in [7] and [15], respectively. Some key parameters adopted in our simulations are presented in Table 1. More information on our MATLAB-based simulator can be found in http://wnt.sjtu.edu.cn/flint/html/index.html. As suggested in [15], the traffic model is assumed to be Poisson distributed with $\lambda^{\text{DL}}(u(k)), k \in \{1, 2, ..., K\}$ taking values from $\{0.1, 0.3, 0.5\}$ packets per UE per second. Besides, $\lambda^{\text{UL}}(u(k)) = 0.5 \times \lambda^{\text{DL}}(u(k))$, as recommended in [7]. The packet size is fixed to be 0.5 Mbytes and packets are independently generated for the DL and the UL.

In Algorithm 1, considering that the DL-to-UL arrival rate ratio is 2/1, we assume that $\alpha^{\text{M,DL}} = \frac{2}{3}$ and $\alpha^{\text{M,UL}} = \frac{1}{3}$. Additionally, we assume that $T = 10$ and $y = 9$ dB, as suggested in some previous work on CRE [12].

In our simulations, after running Algorithm 1, we found that $f^{\text{M,DL}} = 5$, $f^{\text{M,UL}} = 3$, $A^{\text{opt}} = 2$, $f^{\text{S,dynTDD}} = 5$, and approximately 1/3 of macrocell UEs are off-loaded to small

cells. Thus, 5 subframes of every 10 subframes are used as dynamic TDD subframes in small cells.

Based on such results, we investigate the performance of the following 6 schemes in terms of 50/5-percentile UPTs for the DL and the UL, where according to [15], UPT is defined as the ratio of successfully transmitted bits over the time consumed to transmit the said data bits. Note that the consumed time starts when the DL/UL packet arrives at the UE DL/UL buffer and ends when the last bit of the DL/UL packet is correctly decoded.

1) Baseline static TDD scheme: macrocell (DL/UL subframe ratio = 7:3), small cell (DL/UL subframe ratio = 7:3). Note that the assumed TDD DL/UL subframe splitting optimally matches the ratio of DL/UL traffic arriving rates in case of $T = 10$.

2) Straightforward dynamic TDD scheme: macrocell (DL/UL subframe ratio = 7:3), small cell (dynamic TDD without CRE and ABS operations). Note that a DL and UL load balance criterion similar to (8) is used to determine the dynamic TDD DL/UL subframe splitting for the small cells with the constraint in current 3GPP specifications that the lowest and highest DL/UL subframe ratios are 2/3 and 9/1, respectively [7].

3) Static TDD scheme with CRE and ABS operations: macrocell (DL/ABS/UL subframe ratio = 5:2:3), small cell (DL/UL subframe ratio = 7:3). Note that the scheduling policy in [12] is adopted that DL packets of ER UEs should be scheduled with a high priority in subframes overlapping with the macrocell ABSs and that they should not be scheduled in subframes overlapping with the macrocell DL subframes.

4) Proposed scheme with macrocell (DL/ABS/UL subframe ratio = 5:2:3), small cell (DL/dynamic TDD subframe ratio = 5:5), dynamic TDD reconfiguration per T subframes, no IC.

5) Scheme 4) plus small cell DL to macrocell UL IC.

6) Scheme 5) plus small cell DL to small cell UL IC.

Fig. 2 and Fig. 3 show network performance in terms of the DL and the UL 50/5-percentile UPTs, respectively. Moreover, the UPT results are broken down to show the contributions from the macrocell and the small cell tiers.

Comparing the baseline scheme (Scheme 1) with the straightforward dynamic TDD in the small cell tier (Scheme 2), it is easy to conclude that the latter will practically lead to system failure in the UL because of the overwhelming DL-to-UL interference. Similar observations have been reported in [7]. Besides, the overall DL communication in the small cell tier is also in trouble due to resource shortage in the DL caused by massive retransmissions required in the UL.

Comparing the baseline scheme (Scheme 1) with the static TDD scheme with CRE and ABS operations (Scheme 3), it can be seen that large performance gains can be achieved in all performance categories thanks to range expansion and eICIC. More specifically, when the traffic load is low, e.g., $\lambda^{\mathrm{DL}}(u(k)) = 0.1$, about 30-40 % gains in terms of 50-percentile UL and DL UPTs can be achieved mainly due to
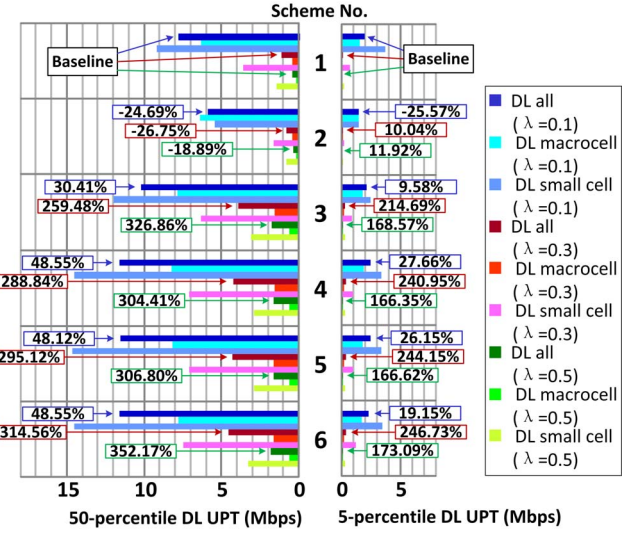

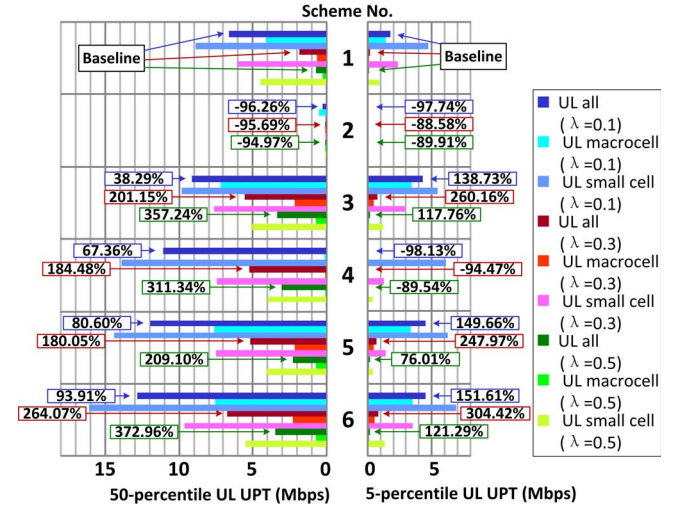
Fig. 2. Performance of DL UPT.

Fig. 3. Performance of UL UPT.

the outsourcing of UEs to small cells and because from time to time non-ER UEs can access the good-quality subframes aligned with macrocell ABSs when such subframes are not used by ER UEs. Besides, a huge gain of around 140 % can be observed for the 5-percentile UL UPT due to the UL interference mitigation properties of range expansion. However, its DL counterpart is much less fortunate, only showing a small performance gain of about 10 %, primarily caused by the poor performance of small cell ER UEs due to DL resource shortage, i.e., ER UE DL transmissions become resource-limited since $A = 2$. When the traffic load is medium to high, e.g., $\lambda^{\mathrm{DL}}(u(k)) = 0.3$ or 0.5, performance gains of Scheme 3 over Scheme 1 in terms of both UL and DL UPTs are much more significant because inter-cell interference is larger and thus the impact of eICIC is more noticeable. In more detail, our simulations show that eICIC leads to remarkable increases of overall UL UPT (approximately 200-360 % for the 50-percentile UPT and 120-260 % for the 5-percentile UPT) and DL UPT (approximately 260-330 % for the 50-percentile

UPT and 170-210 % for the 5-percentile UPT).

As can be further observed from Fig. 2 and Fig. 3, compared with Scheme 3, the proposed schemes (Scheme 4, 5 and 6) achieve superior performances in terms of both 50-percentile and 5-percentile DL UPTs. The additional gains on top of those of Scheme 3 over Scheme 1 are significant when the traffic load is low-to-medium, i.e., $\lambda^{\mathrm{DL}}(u(k))$ =0.1 or 0.3. To be more specific, in terms of 50-percentile DL UPT, additional gains of up to 55 % can be observed when $\lambda^{\mathrm{DL}}(u(k)) = 0.3$, while in terms of 5-percentile DL UPT, additional gains of up to 30 % can be observed for the same case. The reason for these extra gains is that dynamic TDD is able to divert idle UL subframes for DL usage, thus avoiding resource shortage and boosting DL capacity. However, when $\lambda^{\mathrm{DL}}(u(k)) = 0.5$, it is difficult for dynamic TDD to find free UL subframes to be diverted for DL usage, and thus the proposed schemes show comparable performance to Scheme 3. Note that when $\lambda^{\mathrm{DL}}(u(k)) = 0.1$ the proposed schemes successfully enhances Scheme 3 in terms of 5-percentile DL UPT (this was shown to be its weakest performance in the previous paragraph), because in the proposed scheduling policy an ER UE may occupy as many as 5 dynamic TDD subframes for its DL transmission, thus greatly alleviating the DL resource shortage problem.

As for the UL UPT performance of the proposed schemes, when the traffic load is low, extra performance gains in terms of 50-percentile UL UPT of around 30-50 % can be observed for the proposed schemes (Scheme 4, 5 and 6) on top of those for Scheme 3. In contrast, additional performance gains in terms of 5-percentile UL UPT of around 10-15 % can only be observed when the small cell DL to macrocell UL IC is engaged in the proposed Scheme 5 and 6. This shows the need for inter-tier IC to aid the UL of cell-edge UEs at low traffic loads. Moreover, when the traffic load is medium to high, e.g., $\lambda^{\mathrm{DL}}(u(k))$ =0.3 or 0.5, Scheme 3 outperforms the proposed Scheme 4 and Scheme 5 in all categories. due to the negative effect of the small cell DL-to-UL interference, showing that inter-tier IC is helpless in dealing with inter-link interference in the small cell tier. In contrast, the proposed Scheme 6 with double IC, i.e., inter-tier small cell DL to macrocell UL IC and inter-link DL-to-UL IC in the small cell tier, outperforms Scheme 3, providing considerably additional gains of around 65 % 50-percentile UL UPT and 45 % 5-percentile UL UPT at medium traffic loads and some additional gains of around 15 % 50-percentile UL UPT and 5 % 5-percentile UL UPT at high traffic loads. Double IC is thus necessary to aid the UL of cell-edge UEs at medium and high traffic loads.

To sum up, simulation results show that compared with the static TDD scheme with CRE and ABS operations, the proposed scheme achieves strictly superior performances in terms of both 50-percentile and 5-percentile DL UPTs, when the traffic loads are low and medium. No gains are observed at high traffic loads unless the double IC is engaged. Regarding the UL UPT performance, when the traffic load is low, considerable gains in terms of 50-percentile UL UPT can be observed for our proposed schemes compared with the static TDD scheme with CRE and ABS operations. In contrast, gains

in terms of 5-percentile UL UPT can only be expected for our proposed schemes when the small cell DL to macrocell UL IC is engaged. When the traffic load is medium, the proposed scheme can still largely outperform the static TDD scheme with CRE and ABS operations, if the small cell DL to small cell UL IC is further allowed. When the traffic load is high, the proposed scheme with double IC only exhibits marginal performance gain compared with the static TDD scheme with CRE and ABS operations.

V. CONCLUSION AND FUTURE WORK

In this paper, we have investigated small cell dynamic TDD transmissions in HetNets. Based on a novel scheduling policy in small cells, we propose an algorithm to jointly determine UE cell association and macrocell ABS duty cycle, together with another algorithm to split DL/UL subframes in dynamic TDD small cells. From simulation results, we can conclude that significant performance gains can be achieved by introducing dynamic TDD transmissions into HetNets. However, performance gains in the UL of cell-edge UEs significantly depend on traffic conditions and IC capabilities. In order to achieve a competitive 5-percentile UL UPT, small cell DL to macrocell UL IC is necessary when the traffic load is low, while another DL-to-UL IC in the small cell tier is further required when the traffic load is medium or high.

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