On the Feasibility of Blind Dynamic TDD in Ultra-Dense Wireless Networks

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***Abstract*—Dynamic configuring of uplink and downlink switching point in time division duplex (TDD) systems is considered a promising solution to cope with the traffic variations caused by the burstiness of mobile broadband data. However, such dynamic TDD (D-TDD) requires fast inter-cell coordination which may be difficult to implement in ultra-densely deployed networks (UDNs). In order to explore the possibility of designing simplified UDN, we investigate the feasibility of uncoordinated and greedy TDD operation, namely blind D-TDD. It exploits the characteristics of UDN such as low average network utilization and similar transmit power for base stations (BS) and user equipment (UE). To reduce the impact of co-channel interference (CCI), the effect of beamsteering is also evaluated. Our results indicate that blind D-TDD outperforms traditional static TDD (S-TDD) when instantaneous traffic demands for uplink and downlink are highly asymmetric. Also, beamsteering exerts a significant influence on the feasibility of blind D-TDD.**

***Index Terms*—Dynamic TDD; blind; ultra-dense network; throughput.**

I. Introduction

Meeting the continued growth of mobile broadband and the ensuing data tsunami is expected to remain a key driver for operators, vendors, regulators and researchers for many years to come [1], [2]. To address this challenge, a combination of more spectrum, continued densification of access networks and an improved air interface is proposed, where the exact mix will depend on the deployment scenario and intended use case. Among these, the concept of UDNs has gained increasing traction in the wireless community, and is considered one of the main drivers in addressing the traffic demands for 2020 and beyond [3].

Mobile broadband applications and multimedia services prevailing in UDNs are almost by nature discontinuous and bursty, and as such the transmission bandwidth in UL and DL will be asymmetric and vary according to the traffic pattern. To accommodate this burstiness more effectively, D-TDD is considered to be an interesting solution, [4]–[6], and an important component in wireless access system design above 3GHz which includes centimeter- and millimeter-wave bands [7], [8]. Compared to traditional S-TDD where the radio resource allocation depends on average traffic load and transmission bandwidth is fixed, D-TDD is based on instantaneous traffic load in which the switching point between UL and DL in each radio frame is flexible.

On the downside, D-TDD suffers from additional CCI due to the unbalanced allocation of time slots between UL and DL in neighboring cells which does not exist in S-TDD. During the years, there have been many inter-cell coordination techniques proposed to mitigate this cross-slot interference problem, [9]–[11]. Not surprisingly, much of the existing work suggests clear performance benefits of D-TDD for low and medium traffic load. In the case of two links in a local area TDD system, throughput gain is always available regardless of interference as long as the switching point is flexible [12]. By also including power control, it was concluded that similar UL and DL transmit power is beneficial for D-TDD systems in terms of packet delay, especially if interference is not managed [13]. Effort has also been devoted to investigating the feasibility of D-TDD in HetNets [14], sectorized hotspots [15], clusters [16], and enhanced local area (eLA) architectures [17]. However, such dynamic configuration of TDD typically requires real-time inter-cell coordination, which could be difficult to implement in low-cost UDNs.

We envision a wireless access network with massive deployment of low-cost access points for high capacity provisioning in indoor environment. In order to keep the device cost low and to cope with limited backhaul capability, it desirable to minimize the coordination between cells. Thus, it is interesting to examine whether uncoordinated operation of D-TDD is feasible or not. Unlike traditional cellular systems, UDN has characteristics favorable to uncoordinated D-TDD operation. Firstly, it has fewer active users per cell and more load variations. This is due to significantly larger number of BSs and bursty traffic demand, resulting in only a small portion of cells actually transmitting or receiving at any given time. Secondly, BSs and UEs employ similar transmit power, which makes the same-entity interference (BS-to-BS and UE-to-UE) more comparable as opposed to the typical type of UL and DL interference. In [18], the authors report a case where distributed resource allocation shows sufficiently good performance. However, when and where uncoordinated D-TDD is made feasible still remains unknown and necessitates further investigation.

In this paper, we study the feasibility of uncoordinated D-TDD in indoor UDN. In order to make a conservative feasibility analysis, we consider the simplest scheme possible, namely blind D-TDD, where each cell conducts a greedy allocation of resources in a completely uncoordinated manner whenever there is a need for transmission. Performance of blind D-TDD is compared with traditional S-TDD where the UL/DL switching point is determined based on average traffic load. Our investigation also includes the impact of beamsteering of

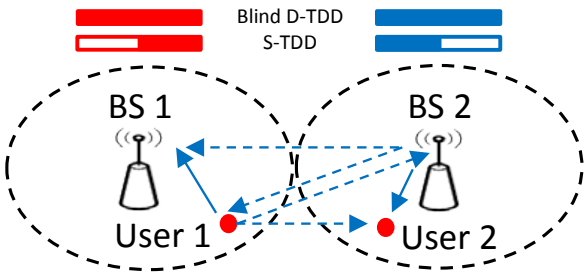

Fig. 1: Resource allocation and interference distribution for S-TDD and blind D-TDD.

BS and UE antennas which allows the beam of the signal to be directed at its intended target and reduce CCI without any inter-cell coordination. Our study will provide insights into the design and deployment of UDN systems, that is to say to which extent blind D-TDD can remain uncoordinated and still perform better than traditional S-TDD.

The remainder of the paper is organized as follows: Section II describes the system model of blind D-TDD and the performance metrics used. Network modeling, setup of the simulation scenario and PHY layer assumptions are detailed in Section III, and Section IV presents the simulation results. Lastly, Section V concludes our analysis.

II. System Model

In a TDMA network with $\mathcal{I} = \{1, \ldots, n\}$ cells, at most a single user is active in each cell in each time slot. At each cell, resources for the time slot are dedicated to either UL and DL and, as such, the user and its associated BS can be said to belong to one of the two disjoint subsets $\mathcal{I}^u$ or $\mathcal{I}^d$ so that $\mathcal{I} = \{\mathcal{I}^u \cup \mathcal{I}^d\}$. Similarly, it follows that the set of active users is given by $\mathcal{I}^a = \{\mathcal{I}^{u,a} \cup \mathcal{I}^{d,a}\}$, where $\mathcal{I}^{u,a} \subset \mathcal{I}^u$ for UL and $\mathcal{I}^{d,a} \subset \mathcal{I}^d$ for DL. System utilization relates the relative load in the network and can be defined as

$$\eta(\mathcal{I}^a) = \frac{|\mathcal{I}^a|}{|\mathcal{I}|} \tag{1}$$

where $|\cdot|$ denotes the cardinality of a set. Note that the maximum number of active users in the denominator is equal to the number of cells in the network $|\mathcal{I}|$.

In S-TDD, a crossing of slots is not permitted. Thus, depending on the cell's current duplex mode, one of the two sets, $\mathcal{I}^u$ or $\mathcal{I}^d$, will reduce to the empty set, $\emptyset$, in the snapshot analysis. Let ρ^d and ρ^u express the portion of DL and UL traffic in the long term, respectively, and $\rho^d + \rho^u = 1$. Then, the resource allocation follows the long-term statistics, i.e.,

$$\Pr(\mathcal{I}^d \neq \emptyset) = \rho^d \text{ and } \Pr(\mathcal{I}^u \neq \emptyset) = \rho^u. \tag{2}$$

In contrast, blind D-TDD claims all the resources in response to the instantaneous traffic demand at each cell. This means that the ratio between $\mathcal{I}^{d,a}$ and $\mathcal{I}^{u,a}$ is equal to the ratio of instantaneous DL and UL traffic. Resource allocation for S-TDD and blind D-TDD is illustrated in Fig. 1 for the two-cell case.

More often than not the limiting factor for throughput in dense networks is inter-cell interference. This interference can be mitigated in cooperative networks when BSs exchange channel state information (CSI) and adapt their transmission accordingly. This is not the case for distributed and non-cooperative networks such as blind D-TDD. Instead, beamsteering which allows directional antennas to be steered towards the intended receiver can be applied. Given the angle of the location for the k:th receiver (θ_k^r), m:th transmitter (θ_m^t), and antenna beamwidth (θ_m^w), the interference region is

$$\delta_{\theta_{km}} := 1_{\{\theta_k^r \leq \theta_m^t \pm \theta_m^w/2\}} \tag{3}$$

Combining Eq. (1) and (3), the signal-to-interference plus noise ratio (SINR) is

$$\gamma_i^{d,a}(\eta) = \frac{P g_{ii}}{\sum_{k \in \mathcal{I}^{d,a} \setminus i} P g_{ki} \delta_{\theta_{ki}} + \alpha \sum_{k \in \mathcal{I}^{u,a}} P g_{ki} \delta_{\theta_{ki}} + \sigma^2} \tag{4}$$

$$\gamma_j^{u,a}(\eta) = \frac{P g_{jj}}{\alpha \sum_{k \in \mathcal{I}^{d,a}} P g_{kj} \delta_{\theta_{kj}} + \sum_{k \in \mathcal{I}^{u,a} \setminus j} P g_{kj} \delta_{\theta_{kj}} + \sigma^2} \tag{5}$$

where P is the transmit power, g_{tr} the path gain between transmitter t and receiver r, $\delta_{\theta_{km}}$ the beamforming constant, σ^2 is noise power, and α an indicator variable so that

$$\alpha = \begin{cases} 1 & \text{if blind D-TDD} \\ 0 & \text{if S-TDD} \end{cases} \tag{6}$$

For a given SINR, achievable user data rate as given by Shannon's capacity formula is

$$R_i^{d,a} = W \log_2(1 + \gamma_i^{d,a}) \tag{7}$$

$$R_j^{u,a} = W \log_2(1 + \gamma_j^{u,a}) \tag{8}$$

with transmission bandwidth W fixed.

The average area throughput defined as the sum of rates follows as

$$TP_{area} = \sum_{i=1}^{|\mathcal{I}^{d,a}|} R_i^{d,a} + \sum_{j=1}^{|\mathcal{I}^{u,a}|} R_j^{u,a} \tag{9}$$

Notice the tradeoff between S-TDD and blind D-TDD. While the achievable user rate is higher in S-TDD due to less interference as shown in Eq. (6), less cells will be active in S-TDD because of the duplexing constraint in Eq. (2).

Average user throughput is computed as the ratio of the average area throughput and the number of active users. We are also interested in the worst case user rate because the same-entity interference could become detrimental to some unfortunate users in blind D-TDD. For this, we examine the 1st percentile point of the cumulative distribution function (CDF)

of all rates, which is more extreme than widely used cell-edge user performance of 5th percentile throughput.

III. Simulation setup

Let us assume an office building with a square shape. A network measures 50×50 meter with BSs placed according to a planned and equally spaced lattice topology. No wraparound is applied to account for border effects for the outermost cells. For indoor scenarios this is rather intuitive as the walls of the building will attenuate much of the surrounding interference anyway.

User locations and the duplex mode of cells are both outcomes of uniform distributions. Monte-Carlo simulation over 1000 realizations is performed according to parameters in Table I to estimate the throughput. Full-buffer load is also assumed. Due to line-of-sight (LOS) between users and BSs, power loss follows the inverse square law which implies that each UE is associated with its closest BS.

In order to compare the relative gains of an increasingly noise-limited environment, antennas with varying degree of directivity is applied to mitigate other-cell interference. The antenna is assumed to be ideal without the presence of side lobes. Other-cell interference originates either from the same source (UE↔UE and BS↔BS) or some other entity (UE↔BS and BS↔UE), [19]. In S-TDD, same-entity interference is avoided by synchronizing the radio frames of the different user groups by applying the same rate of (a)symmetry between DL and UL.

TABLE I: Simulation parameters

Parameter	Value
Number of BSs	25
Number of UEs	$1 \rightarrow 25$
Bandwidth	20 MHz
Frequency	10 GHz
Cell radius	5 m
Transmit power	0 dBm
Frequency reuse factor	1
Antenna gain	0 dBi
BS beamwidth	$360° \rightarrow 0°$
UE beamwidth	$360° \rightarrow 120°$
Noise figure	9 dB
Noise spectral density	-174 dBm/Hz

IV. Numerical Results

In the numerical experiments, we assume that the broadband data is long-term symmetric, i.e., $\rho^d = \rho^u = 0.5$, for brevity. The greedy nature of blind D-TDD will amount to a complete allocation of resources to either UL or DL, where the allocation of twice as many time slots means that the throughput of blind D-TDD is doubled when there is a single user in the system, which is to be expected in the absence of interference. This is demonstrated in Fig. 2, which depicts the average and 1st percentile user throughput for what is in the multi-cell case a function of system utilization. It also shows that blind D-TDD consistently outperforms S-TDD, both in an average sense as well as in the worst case, but with

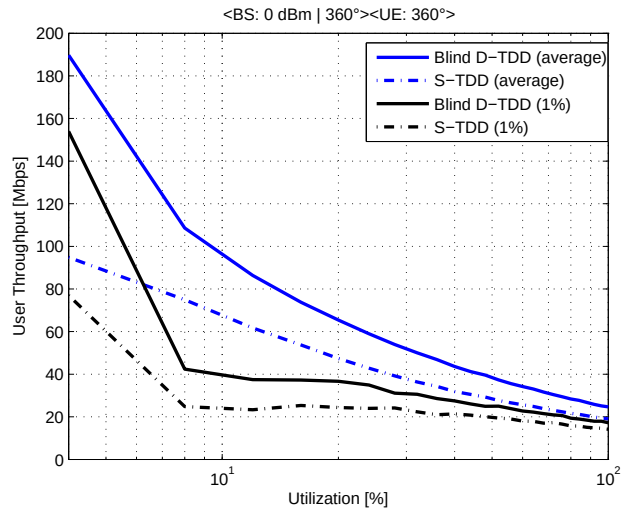

Fig. 2: Average and 1st percentile user throughput.

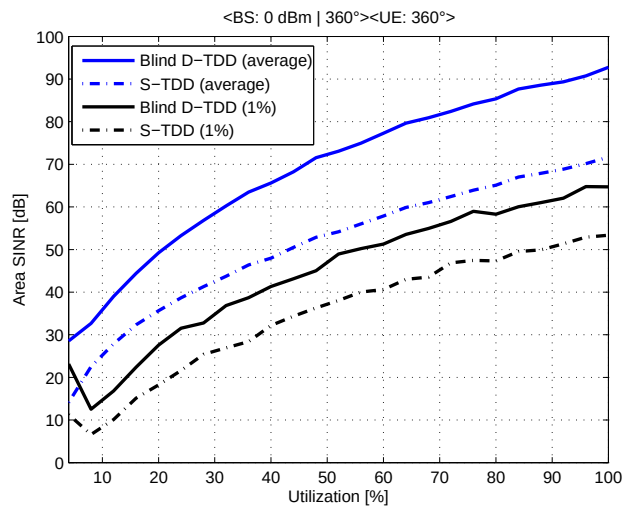

Fig. 3: Average and 1st percentile area SINR.

diminishing gains as the utilization and, hence, interference in the network is increased. Low load regime is defined as around 10% utilization in the network, whereas high load considers 80% utilization. Omni-directional antennas were used for both BSs and UEs. Corresponding average area SINR is given in Fig. 3.

Beamsteering antennas are applied to mitigate CCI and increase the overall data rate. Compared to BSs, UE antennas will have limited beamforming capability due to their lower cost and smaller factor. In subsequent figures, area throughput as a function of antenna beamwidth is depicted under various traffic load. In Fig. 4, blind D-TDD is shown to outperform S-TDD with increasing gains as the beam of the BS transmit antenna narrows around its intended user. This trend is reinforced with 120° beamwidth at the UE side. The gains are however less obvious in Fig. 5 which depicts the exact same setup but in high load regime. As the beamforming improves at the BS side, S-TDD becomes increasingly noise-limited in

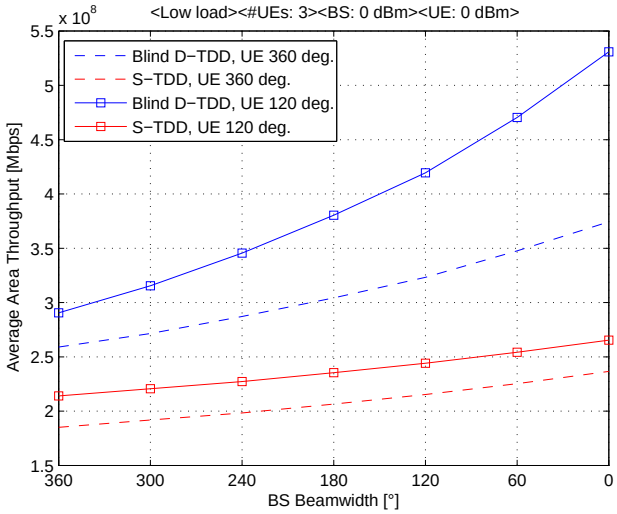

Fig. 4: Throughput and BS beamwidth in low load regime.

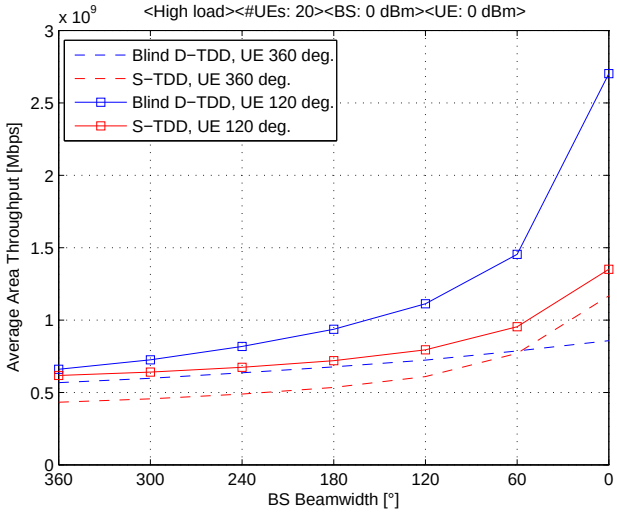

Fig. 5: Throughput and BS beamwidth in high load regime.

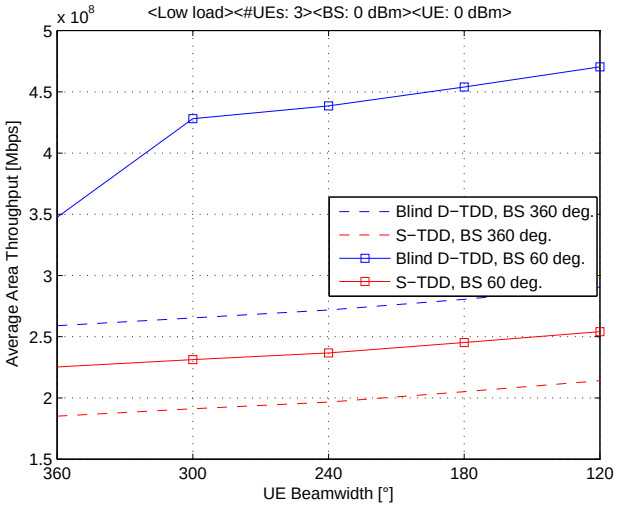

Fig. 6: Throughput and UE beamwidth in low load regime.

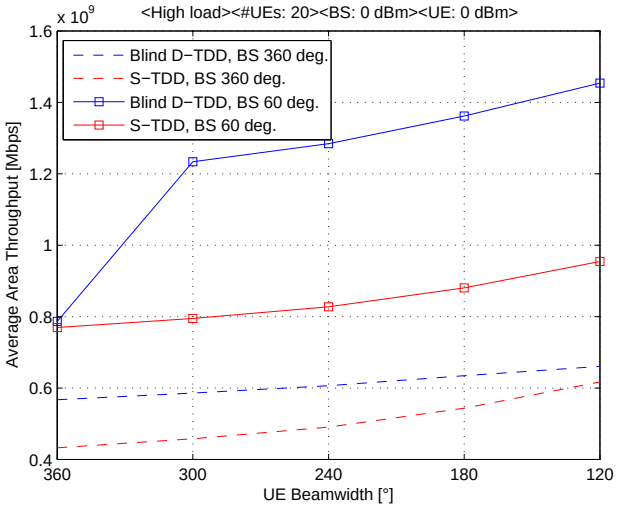

Fig. 7: Throughput and UE beamwidth in high load regime.

the DL and comparably better than blind D-TDD for a certain BS beamwidth. The order is restored if 120° beamwidth again is assumed at the UE side.

In Fig. 6 and 7, we instead control the beamwidth of the transmitting UE antennas for different load, steer it towards its intended target, and observe the difference. In both aforementioned figures, blind D-TDD consistently outperforms S-TDD, and improving antennas only at the UE side is not enough to put S-TDD over the top.

The impact of path loss on average user data rate in high load regime is depicted in Fig. 8. Not surprisingly, both blind and static D-TDD experience increasing gains as interference is reduced due to the increase in path loss. The gain is however more pronounced for blind D-TDD since it induces more interference into the network than S-TDD, both in terms of more other-entity interference as well as same-entity interference which does not exist in S-TDD mode.

V. Conclusion

In this paper, we investigated the feasibility of employing blind D-TDD in an ultra-densely deployed network. The extremely low user density and burstiness of mobile data traffic motivates dynamic duplexing where resources can be allocated according to varying traffic conditions and channel rates. The fact that BSs may outnumber users suggests that a blind transmission scheme can be employed in which the user in each cell is greedily allocated as much resources as needed for the transmission without any coordination whatsoever.

Results show clear advantages of blind D-TDD compared to traditional S-TDD in UDN for both average and worst case cell-edge users when 0 dBm transmit power and omni-directional antennas are used, especially in low- and medium load regime. In high load, users experience diminishing gains as the interference in the network is increased. Nevertheless, thanks to the allocation of twice as many time slots compared to S-TDD, blind D-TDD is still found to perform comparably

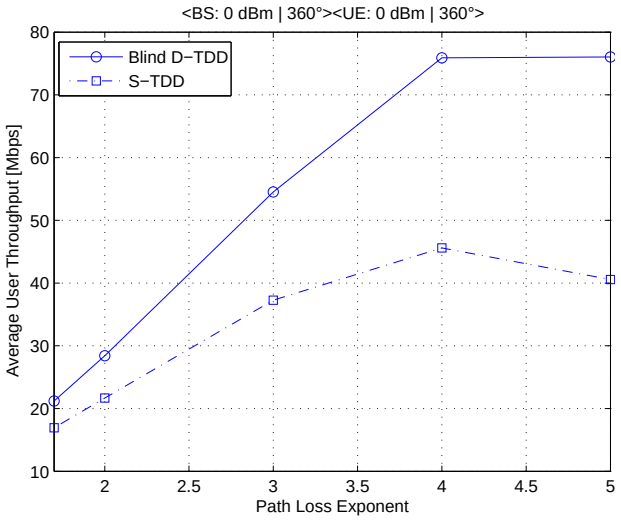

Fig. 8: User throughput and path loss.

better.

To mitigate other-cell interference from neighboring BSs and increase the data rate, beamsteering is adopted for BS and UE antennas. It is shown that reducing DL interference through BS beamforming helps make S-TDD increasingly noise-limited in that particular direction to the extent that S-TDD will outperform blind D-TDD unless beamforming is also applied for the transmitting UEs. On the other hand, only improving beamforming for the UEs but not the BS antennas is not enough for S-TDD to outperform blind D-TDD, irrespective of the load.

Experimenting with the network size was shown not to be a factor in our results. It is also worth mentioning that all of the considered cases assumed 0 dBm transmit power, implying that UEs have a considerable impact on the interference distribution in the network. Future work could therefore include transmit power control in which some degree of cooperation between BSs is permitted. Furthermore, path loss in free space provides a rather conservative estimate on the performance gain and therefore feasibility of blind D-TDD. A more realistic path loss model that better models the propagation environment indoor by also including shadowing is desirable.

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