Gao et al. EURASIP Journal on Wireless Communications and Networking (2017) 2017:91
DOI 10.1186/s13638-017-0877-4

EURASIP Journal on Wireless Communications and Networking

RESEARCH Open Access

Service- and interference-aware dynamic TDD design in 5G ultra-dense network scenario

Weidong Gao*, Binyong Lin and Gang Chuai

Abstract

The 5G wireless communication system supports varied applications, making the uplink/downlink traffic asymmetry more and more serious. Dynamic time division duplex (TDD) technique has become a key technology of 5G networks due to its flexibility to support asymmetric services. In this paper, we study dynamic TDD sub-frame reconfiguration algorithm based on shifting. Firstly, we define cell shifting priority considering both traffic and interference. Then, we perform cell shifting-based TDD sub-frame reconfiguration following cell shifting priority. Simulation results show that the proposed dynamic TDD algorithm can guarantee high data rate and low interference, thus effectively increases the network throughput.

Keywords: 5G, Traffic, Interference, Dynamic TDD, Adaptive

1 Introduction

In order to adapt to the explosive growth of mobile data in the future and speed up the application of new services, the 5th generation (5G) of mobile communication technologies came into being. So far, the vision and demand of 5G communication has been clear, while how to integrate a variety of new technologies and existing technologies to achieve an integrated 5G network has become the focus of the current research.

5G is considered to be a converged network, many key technologies studied in recent years, e.g., cognitive radios and millimeter-wave communications, will be applied in 5G systems [1–3]. An important characteristic of 5G system is the ultra-dense network deployment. In an ultra-dense 5G network, a single cell can only serve limited number of users, and the traffic of each cell varies greatly and fluctuates dynamically, which makes the fixed time division duplex (TDD) frame configuration strategy cannot meet the needs of different cells in different time periods. The dynamic TDD technology can be used to change the frame configuration of the cell dynamically to adapt to the varied uplink and downlink traffic, so as to improve the overall system throughput [4]. With dynamic TDD technology, the adjacent cells may use different TDD frame configuration because of variant traffic requirements, leading to opposite transmission directions (uplink or downlink) by these cells. For example, as illustrated in Fig. 1, cell #4 will also receive the downlink signals from cell #2 during its uplink reception, which will cause cell-cell interference. Similarly, the UE #2 will also receive the uplink signals from UE #4 during its downlink reception, which will cause UE-UE interference. The referred cell-cell interference and UE-UE interference are called cross-slot interference, which do not exist in traditional synchronized networks with aligned downlink/uplink transmission and reception.

With the newly introduced cross-slot interference as mentioned above, it is recognized the interference problem in dynamic TDD system is more serious than that of traditional LTE networks. In particular, the uplink reception performance may deteriorate dramatically for the reason that the base stations have greater transmission power and will lead to more cross-slot interference [5]. Therefore, it is necessary to design proper dynamic TDD schemes that can effectively reduce the cross-slot interference and ensure the system throughput. Otherwise, the throughput loss caused by cross-slot interference may outweigh the throughput gain brought by dynamic TDD.

* Correspondence: gaoweidong@bupt.edu.cn
Beijing University of Posts and Telecommunications, Beijing 100876, China

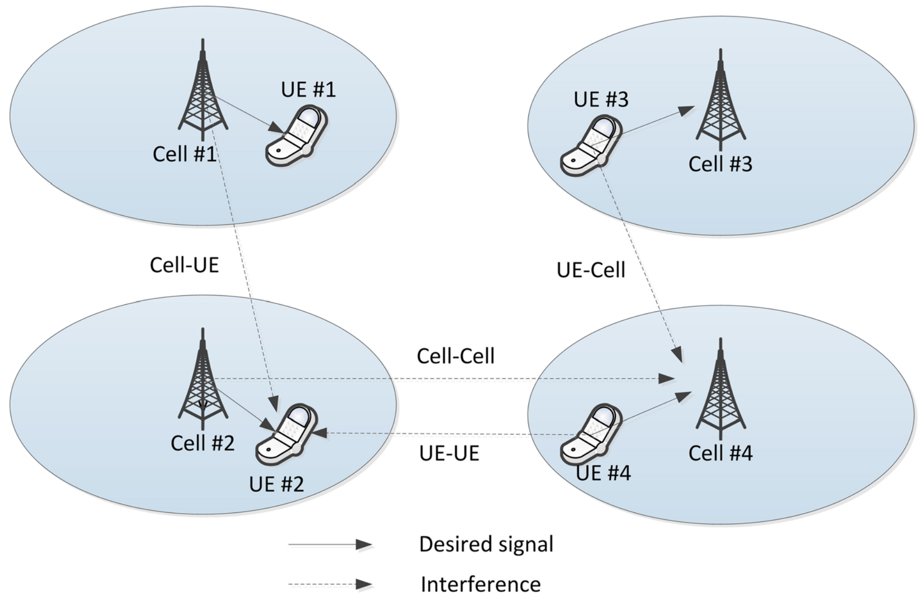

Fig. 1 Cross-slot interference introduced by dynamic TDD

In addition to cross-slot interference problems, the dynamic TDD also needs to consider the interference and traffic balance. For dynamic TDD, the ideal situation is to allocate uplink and downlink resources in proportion to their traffic volume. However, it is not enough to consider only the amount of traffic. If the interference is not carefully addressed, the system throughput may be seriously affected. Therefore, the uplink and downlink sub-frame reconfiguration scheme must take into account both the network traffic and network interference level to maximize the system throughput. As we know, 5G traffic has the characteristics of burst and fluctuation with time. At the same time, 5G traffic also has time correlation, which is stable in a certain period of time. Therefore, we should consider the unification of historical data and instantaneous data when considering traffic volume. To sum up, we need to combine the traffic characteristics and the interference levels to design a reasonable dynamic TDD scheme.

Literatures have studied varied dynamic TDD schemes, including the proportion method, greedy method, evolutionary game method, and soft reconfiguration method. For the proportion method [6], the TDD frame configuration whose UL/DL sub-frame ratio is closest to the UL/DL traffic ratio is adopted. The commonly used proportion method includes traffic volume-based schemes [7, 8] and buffer-based schemes [9–11]. The proportion method is simple, but it cannot fully reflect the needs of the network because it does not take into account the order of UL/DL sub-frames. Due to its simplicity, the proportion method is often used as the baseline scheme to measure the performance of newly proposed dynamic TDD schemes. The greedy method [12, 13] firstly calculates the gain of each sub-frame supposing it is an uplink sub-frame or a downlink sub-frame and configures the sub-frame following the direction that with larger gain. The greedy method is able to adapt to the instantaneous network load, but it might not be optimal during a long period of time. The central idea of evolutionary game algorithm [14] includes "choice" operation and "mutation" operation. A player (corresponding to a home base station) chooses its TDD frame configuration based on the utility function where the policy with greater utility function will be chosen with higher probability.

The soft reconfiguration method [15] reconfigures TDD frame configuration following a transition diagram, where for a cell, if the received interference from other cells is greater than a threshold, it will choose from the TDD frame configurations along the left direction of the transition diagram, and if the interference it introduces to other cells is larger than a second threshold, it will choose from the TDD frame configurations along the right direction of the transition diagram. Soft reconfiguration method can ensure that all the cells have a good SINR and therefore reduce the interference of the entire network. Moreover, because the difference between the adjacent frame configurations is small, the negative effect of frame reconfiguration is neglectable, which is helpful to the stability of the network. However, the soft reconfiguration method has two shortcomings that need to be enhanced. First, there may be a situation that the given two conditions are satisfied at the same time, i.e., a cell receives serious interference while it also introduces serious interference to other cells. When this happens, it is impossible to determine whether the TDD frame configuration should shift to left or to right along the transition diagram. Second, there is a probability that a cell is continuously receiving heavy interference from other cells under current TDD frame configuration, but it will cause severe interference to other cells when it shifts its TDD frame configuration along the right direction of the transition diagram, therefore resulting in back and forth reconfiguration between these two TDD frame configurations.

Inspired by the soft reconfiguration method, we in this paper propose an improved TDD frame configuration scheme based on shifting. In the proposed scheme, the cells are divided into groups, and it is regulated that the cells in each group can only shift along the same direction. At the same time, we also define the shifting priority, which is set according to the interference and traffic volume. These regulations ensure the practicability of the soft reconfiguration scheme.

2 System model

Consider a clustered network architecture, where the cells with severe cross-slot interference are distributed to the same cell cluster and share the same TDD frame configuration. Commonly used clustering methods include threshold method [16–18] and heuristic algorithm [19]. Without losing generality, we use a threshold method that based on link coupling loss [17]. Taking a single cell cluster B as an example, assume that there are a total of N cells in the cluster and M_i users in cell #i.

Assume that a radio frame is composed of T sub-frames, and we use DL/UL sub-frame number to represent DL/UL data volume. For cell $i \in B$, the downlink sub-frame number l_i can be determined by a formula (1) if only the traffic volume is considered when designing dynamic TDD frame configuration scheme.

$$l_i = \left\lceil \frac{\sum_{j=1}^{M_i} Q_j^{DL}(t)/C_j^{DL}}{\sum_{j=1}^{M_i} Q_j^{UL}(t)/C_j^{UL} + \sum_{j=1}^{M_i} Q_j^{DL}(t)/C_j^{DL}} \cdot T \right\rceil \tag{1}$$

where $\lceil x \rceil$ is the ceiling function, $Q_j^{UL}(t)$ and $Q_j^{DL}(t)$ are the uplink and downlink data buffer size, and C_j^{UL} and C_j^{DL} are the UE's average UL/DL throughput in its last TDD reconfiguration cycle. We can see from formula (1) that the number of downlink sub-frame is proportional to the downlink data buffer size of the cell and inversely proportional to the average throughput of last TDD reconfiguration cycle. Because the instantaneous buffer size and average throughput may be different, the downlink sub-frame requirements are usually different among the cells.

When cell clustering is adopted, all the cells in the same cluster have the same TDD frame configuration. If we only consider the UL/DL data rather than the interference, the downlink sub-frames required in a radio frame can be expressed as:

$$l = \left\lceil \frac{\sum_{i=1}^{N}\sum_{j=1}^{M_i} Q_j^{DL}(t)/C_j^{DL}}{\sum_{i=1}^{N}\sum_{j=1}^{M_i} Q_j^{UL}(t)/C_j^{UL} + \sum_{i=1}^{N}\sum_{j=1}^{M_i} Q_j^{DL}(t)/C_j^{DL}} \cdot T \right\rceil \tag{2}$$

At any time t, assume there are N_{UL}^t cells being uplink slot and N_{DL}^t cells being downlink slot, we know that $N_{\mathrm{UL}} + N_{\mathrm{DL}} = N$. The UL/DL SINR of user #j in cell #i at moment t is:

$$\mathrm{SINR}_{UL}(j,i,t) = \frac{P_{UE-Cell}(j,i)h_{j,i}}{\sum_{k=1}^{N_{\mathrm{DL}}^t}\sum_{m'=1}^{M_k} P_{UE-Cell}(m',i)h_{m',i} + \sum_{l=1,l\neq i}^{N_{UL}^t} P_{Cell-Cell}(l,i)h_{l,i} + N_0}$$
$$\mathrm{SINR}_{DL}(i,j,t) = \frac{P_{Cell-UE}(i,j)h_{i,j}}{\sum_{k=1,k\neq i}^{N_{DL}^t} P_{Cell-UE}(k,j)h_{k,j} + \sum_{l=1}^{N_{UL}^t}\sum_{m=1}^{M_l} P_{\mathrm{UE}-UE}(m,j)h_{m,j} + N_0} \tag{3}$$

where $P(k,j)$ is the transmit power of node #k to node #j; $h_{k,j}$ is the channel gain including antenna gain, path loss, shadow fading, and penetration loss; N_0 is the noise power. Here, a node may be a cell or a UE.

If the number of downlink sub-frame of cell #i is ω_i, the worst DL/UL SINR of cell #i at time t can be expressed as:

$$\mathrm{SINR}_{\min}^{UL}(i,t) = \min_{j=1,2,\ldots,M_k}\{SINR_{UL}(j,i,t)\}, \omega_i \leq t < T$$
$$\mathrm{SINR}_{\min}^{DL}(i,t) = \min_{j=1,2,\ldots,M_k}\{SINR_{DL}(i,j,t)\}, 0 \leq t < \omega_i \tag{4}$$

Then the worst SINR of cell #i in a radio frame is:

$$SINR_{\min}^{i} = \min\{SINR_{\min}^{\mathrm{UL}}(i,0), \ldots, SINR_{\min}^{UL}(i,\omega_i-1), SINR_{\min}^{\mathrm{DL}}(i,\omega_i), \ldots, SINR_{\min}^{DL}(i,T-1)\} \tag{5}$$

Assume that a base station's transmit power is much larger than that of an UE, so cell-cell interference is usually much severe than UE-UE interference. To simplify, we assume that the worst SINR exists in uplink, i.e., the formula (5) can be reduced to:

$$SINR_{\min}^{i} = \min\{SINR_{\min}^{UL}(i,\omega_i), \ldots, SINR_{\min}^{UL}(i,T-1)\} \tag{6}$$

If a cell is able to transmit data successfully in a radio frame, the worst SINR should be no less than the threshold Thres, that is:

$$SINR^i_{\min} \geq \text{Thres} \tag{7}$$

The following conditions should be met for the cells in a whole cluster that can transfer data normally within a cluster:

$$\min_{i=1,2,\dots N} \left(SINR^i_{\min}\right) \geq \text{Thres} \tag{8}$$

Based on the formula (8), we can design the corresponding dynamic TDD configuration scheme, which will be detailed in the next section.

3 Dynamic TDD frame configuration scheme

In this paper, we propose a shifting-based TDD frame configuration scheme. The cells in a cluster are divided into three groups: left-shifting group, right-shifting group, and non-shifting group, and the cells in each group can only shift along the same direction, i.e., left or right. Furthermore, the shifting operations follow shifting priority rules.

3.1 Shifting priority

Every cell has a shifting priority, which is used to indicate the processing order of the corresponding cell, i.e., the cell with higher shifting priority can prioritize its TDD frame configuration. The cell shifting priority is composed of two parts: the interference priority part and the service priority part. The interference priority is defined as the worst SINR deviation from the SINR threshold (it should be ensured that the worst SINR of a cell should be greater than the SINR threshold). The higher the interference priority is, the easier it can meet the requirements of the interference conditions and the greater it can contribute to the cell shifting priority. The service priority indicates how close the radio frame configuration is to the traffic; the higher the service priority is, the easier it can satisfy the requirement of the traffic and the greater it can contribute to the cell shifting priority.

We know that the more downlink sub-frames a cell uses, the stronger its anti-interference ability is and the more interference it will bring to other cells. For a low SINR cell, it is better to increase the downlink sub-frames to enhance its anti-interference ability, and we use its neighboring cell's worst SINR reduction as the interference priority, which is denoted as S^i_R. Similarly, for a high SINR cell, we should reduce its downlink sub-frames to reduce the interference to adjacent cells, and we use its worse SINR reduction as the interference priority, which is denoted as S^i_L.

The service priority is relevant to the traffic volume and cell clustering strategy, considering that it is not deterministic whether l_i or l is larger and there are two situations when calculating the service priority: (1) If l_i is larger than l, improving the service priority is equivalent to increasing the number of downlink sub-frames, which is denoted as Traffic^i_R; (2) if l_i is smaller than l, improving the service priority is equivalent to decreasing the number of downlink sub-frames, which is denoted as Traffic^i_L.

When the interference priority and the service priority are jointly considered, the shifting priority calculation can be divided into two cases: (1) If there are few downlink sub-frames, we need to increase the downlink sub-frames to increase the shifting priority Prior^i_R that is determined by S^i_R and Traffic^i_R; (2) if there are excessive downlink sub-frames, we need to decrease the downlink sub-frames to decrease the shifting priority Prior^i_L that is determined by S^i_L and Traffic^i_L.

3.1.1 Case 1: shifting priority calculation when increasing downlink sub-frames

Assume the downlink sub-frame number of cell #i is ω_i, and we will calculate its cell shifting priority Prior^i_R when its downlink sub-frames increase to $\omega_i + 1$, where $1 \leq \omega_i < T - 1$.

Firstly, we will calculate S^i_R. It is known that a cell's worst SINR value will become larger when its downlink sub-frames increase, and at the same time, other cells' worst SINR values will become smaller. So, we need to evaluate to what degree the neighboring cells' worst SINR deteriorate by increasing a cell's downlink sub-frames. We use $\text{SINR}_{\min^{ik}}$ to denote the worst SINR of cell k $(k \neq i)$ after cell i increases its downlink sub-frames, and we have:

$$SINR^{ik}_{\min} = \min\left\{SINR^k_{\min}, SINR^{UL}_{\min}(k,t)\right\} \leq SINR^k_{\min} \tag{9}$$

For cell #k, the more $\text{SINR}^k_{\min}$ is near to Thres, the more serious its worst SINR will be. Define $\Delta\text{SINR}_{R^{ik}}$ as the worst SINR reduction by deducing downlink sub-frames of cell i:

$$\Delta SINR^{ik}_R = \frac{SINR^k_{\min} - SINR^{ik}_{\min}}{SINR^k_{\min} - Thres} \tag{10}$$

It is obvious that $1 \geq \Delta\text{SINR}_{R^{ik}} \geq 0$, where $\Delta\text{SINR}_{R^{ik}} = 0$ means that the worst SINR of cell #k will not deteriorate and $\Delta\text{SINR}_{R^{ik}} = 1$ means that the worst SINR of cell #k will decrease to Thres, which is the worst case among the viable options. $\Delta\text{SINR}_{R^{ik}} > 1$ indicates that the worst SINR of cell #k is lower than the threshold and it is not a viable option.

Interference priority is related to the SINR deterioration when increasing the downlink sub-frames of cell #i. The smaller the SINR deterioration, the greater S^i_R

will contribute to the shifting priority. S_R^i can be calculated as follows:

1. If $\Delta\mathrm{SINR}_{R^{ik}} < 1$, S_R^i is a viable option and a finite positive number. The closer to 0 the value of $\Delta\mathrm{SINR}_{R^{ik}}$ is, the bigger the S_R^i will be; the closer to q the value of $\Delta\mathrm{SINR}_{R^{ik}}$ is, the smaller the S_R^i will be. It is ideal that all $\Delta\mathrm{SINR}_{R^{ik}}$ values stay away from 1, i.e., the closer to 1 the value of $\Delta\mathrm{SINR}_{R^{ik}}$ is, the greater it will impact on S_R^i. Considering this characteristic, we use harmonic mean value for S_R^i.
2. If $\Delta\mathrm{SINR}_{R^{ik}} = 1$, S_R^i is the worst case among the viable options, whose value is 0.
3. If $\Delta\mathrm{SINR}_{R^{ik}} > 1$, S_R^i is not a viable option and it has a negative value.

According to the above analysis, the formula of S_R^i can be obtained:

$$S_R^i = \begin{cases} \dfrac{N-1}{\sum\limits_{k=1,k\neq i}^{N} \dfrac{1}{1-\Delta SINR_R^{ik}}}, & \max\left(\Delta SINR_R^{ik}\right) < 1 \\ 0, & \max\left(\Delta SINR_R^{ik}\right) = 1 \\ -1, & \max\left(\Delta SINR_R^{ik}\right) > 1 \end{cases} \tag{11}$$

Traffic priority $\mathrm{Traffic}_R^i$ is related to the traffic state of cell #i when the downlink sub-frames increase, which can be expressed as:

$$Traffic_R^i = \frac{l_i - l}{|l_i - \omega_i - 1|} \tag{12}$$

Considering there are cases that $\omega_i > l_i$, we use absolute value that is adopted for the denominator of the formula (12). Due to that $l_i > l$, $\mathrm{Traffic}_R^i > 0$ holds. The greater the value of $\mathrm{Traffic}_R^i$ is, the more accurate it can reflect the actual traffic needs, and the greater the shifting priority will be.

The shifting priority of cell $i \in B_R$ when its downlink sub-frames become from ω_i to $\omega_i + 1$ can be expressed as:

$$Prior_R^i = \begin{cases} S_R^i \cdot Traffic_R^i, & 1 \le \omega_i < T-1 \\ -1, & Others \end{cases} \tag{13}$$

3.1.2 Case 2: shifting priority calculation when decreasing downlink sub-frames

Assume the downlink sub-frame number of cell #i is ω_i, and we will calculate its shifting priority Prior^i when its downlink sub-frames decrease to $\omega_i - 1$, where $1 \le \omega_i < T - 1$.

Firstly, we will calculate S_L^i. It is known that a cell's worst SINR value will become smaller when its downlink sub-frames decrease, and at the same time, other cells' worst SINR values will become larger. So we need to evaluate to what degree the cell' worst SINR deteriorate by decreasing its downlink sub-frames. We use $\mathrm{SINR}_{\min^{ii}}$ to denote the worst SINR of cell i after it decreases its downlink sub-frames, and we have:

$$SINR_{\min}^{ii} = \min\left\{SINR_{\min}^{i}, SINR_{\min}^{\mathrm{UL}}(i,t)\right\} \le SINR_{\min}^{i} \tag{14}$$

Define $\Delta SINR_L{}^{ii}$ as the worst SINR reduction by deducing its downlink sub-frames:

$$\Delta SINR_L^{ii} = \frac{SINR_{\min}^{i} - SINR_{\min}^{ii}}{SINR_{\min}^{i} - Thres} \tag{15}$$

We can get the interference priority S_L^i as follows:

$$S_L^i = \begin{cases} 1-\Delta\mathrm{SINR}_L^{ii}, & \max\left(\Delta\mathrm{SINR}_R^{ii}\right) \le 1 \\ -1, & \max\left(\Delta\mathrm{SINR}_R^{ii}\right) > 1 \end{cases} \tag{16}$$

The traffic priority $\mathrm{Traffic}_L^i$ when the downlink sub-frames decrease is:

$$Traffic_L^i = \frac{l - l_i}{|l_i - \omega_i + 1|} \tag{17}$$

The shifting priority of cell $i \in B_L$ when its downlink sub-frames decrease from ω_i to $\omega_i - 1$ can be written as:

$$Prior_L^i = \begin{cases} S_L^i \cdot Traffic_L^i, & 1 < \omega_i \le T-1 \\ -1, & Others \end{cases} \tag{18}$$

After obtaining the shifting priority that is determined by both of the interference priority and the traffic priority, if we want to increase the downlink sub-frames, we can choose the cell with the maximum Prior_R^i value, and if we want to decrease the downlink sub-frames, we can choose the cell with the maximum Prior_L^i value.

3.2 Dynamic TDD frame configuration

For the dynamic TDD frame configuration method based on traffic and interference, we give priority to increasing the downlink sub-frames for cells with high Prior_R^i and decreasing the downlink sub-frames for cells with high Prior_L^i. The TDD frame configuration includes the following processes.

3.2.1 Cell set partition

For the shifting-based dynamic TDD scheme, the cells in a cluster are firstly partitioned into three groups according to different shifting directions: left-shifting group B_L,

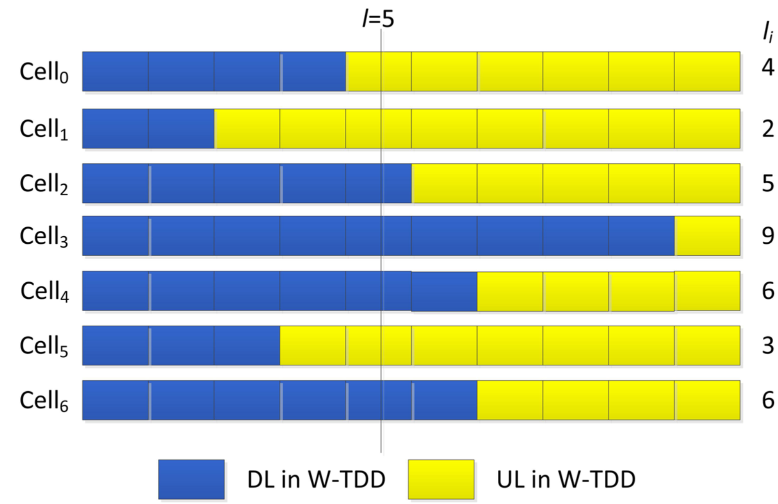

Fig. 2 Example of cell set partition

right-shifting group B_R, and non-shifting group B_M. The cells in each group can only shift along single direction, i.e., left or right. For simplicity, the following assumptions are adopted [20, 21]:

1. Both the uplink sub-frames and downlink sub-frames are continuous; furthermore, the downlink sub-frames are in front of the uplink sub-frames.
2. For any TDD configuration, there is at least one uplink sub-frame and one downlink sub-frame, so that there is traffic in the downlink direction and uplink direction at any time, i.e., $\omega_i \in \{1, 2, \ldots, T-1\}$.

Take Fig. 2 for example: the blue rectangles represent downlink sub-frames and the red rectangles represent uplink sub-frames. The relationships between l_i and l are also illustrated in the figure. According to the numerical relationship between l_i and l, the partition of the cell set is as follows:

$$\begin{array}{ll} B_M = \{Cell_2\}, & \text{where } l_i = l \\ B_R = \{Cell_3, Cell_4, Cell_6\}, & \text{where } l_i > l \\ B_L = \{Cell_0, Cell_1, Cell_5\}, & \text{where } l_i < l \end{array} \quad (19)$$

We do not deal with the cells in the non-shifting group, and we shift to the right for the cells in the right-shifting group and shift to the left for the cells in the left-shifting group. Next, we will obtain the right shifting priority Prior_R^i and left shifting priority Prior_L^i, respectively.

3.2.2 Right shifting and left shifting

As depicted in Fig. 3, cell $i \in B_R$ means that the number of downlink sub-frames will change from ω_i to $\omega_i + 1$, where $1 \leq \omega_i < T - 1$.

We will choose proper cells from the right-shifting group to move them to the right. Firstly, we need to calculate the right shifting priority for all the cells within the group. Right shifting priority has taken into account the factors of traffic and interference, and the right shifting operation will increase the interference to other cells and reduce the interference to itself. The value of Prior_R^i may be positive, zero, or negative. Positive value means that the right shifting operation will make the network performance better, negative value means the opposite, and zero value indicates that the gain and loss are balanced.

After obtaining the right shifting priority Prior_R^i for the cells in the right-shifting group, we will choose the cells following the right shifting selection criterion, which is as follows:

1. If $\max\left(\text{Prior}_R^i\right) > 0$ holds for all cells in the right-shifting group, the cell with maximal Prior_R^i will be

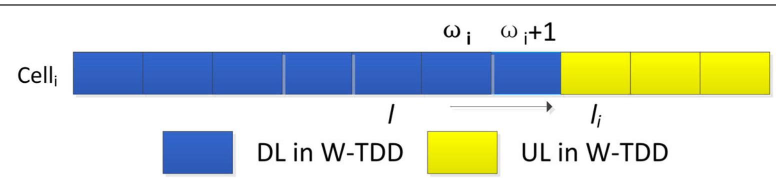

Fig. 3 Right shifting example

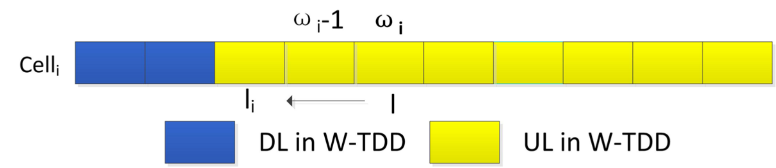

Fig. 4 Left shifting example

selected. If there are more than one cell meet this condition, select one from them randomly.

2. If $\max\left(\mathrm{Prior}_R^i\right) = 0$, then select the cell with the smallest impact on other cells' SINR by right shifting operation.
3. If $\max\left(\mathrm{Prior}_R^i\right) < 0$, ignore the right shifting operation.

As shown in Fig. 4, cell $i \in B_L$ means that the number of downlink sub-frames will change from ω_i to $\omega_i - 1$, where $1 < \omega_i \le T - 1$.

Similar to the right shifting operation, we can compute the left shifting priority for the cells in B_L. Left shifting priority also needs to consider the amount of traffic and interference, because the left shifting operation will reduce the interference to other cells and increase the interference to themselves. After obtaining the left shifting priority, we can select the cell from B_L that needs to shift left. The left-shifting cell selection principle is similar to that of the right shifting priority, which is omitted here.

3.2.3 Shifting flow

With respect to the proposed dynamic TDD scheme based on traffic and interference, we give the flows of shifting as follows:

Step 1: Obtain the downlink sub-frame numbers l_i and l according to formulas (1) and (2). Partition the cells into three groups: left-shifting group B_L, right-shifting group B_R, and non-shifting group B_M.
Step 2: If the corresponding interference is small for l_i, i.e., it meets the condition of formula (8), then the shifting strategy which coincides with the W-TDD method [19] is adopted, and if the corresponding interference for l is too big, the C-TDD method is adopted. In all other cases, shifting-based dynamic TDD is used.
Step 3: The initial state is the same as that of W-TDD method.
Step 4: Calculate the right shifting priority according to the formulas (9)~(13) and perform right shifting operation following the principle of right shifting.
Step 5: Calculate the left shifting priority according to the formulas (14)~(18) and perform left shifting operation following the principle of left shifting.
Step 6: Iterate step 3 and step 4 until the condition of formula (8) is met for all cells.

4 Simulation results

4.1 Simulation parameters

We have constructed dynamic system level simulation platform based on VC++ referencing the enhanced small cell deployment scenario [22, 23], and the simulation parameters are listed in Table 1. FTP model 1 service model is used and the FTP packet size is 0.5 M bytes. The dynamic TDD reconfiguration cycle is set to 40 ms [24]. The UEs move in random directions within the simulation area with the preset speed. The performance evaluation is carried out from two aspects: SINR and average packet throughput, where packet throughput is defined as the ratio of the file size to the transmission time, including queuing time and the packet transmission time. In the simulation, low ($\lambda_{\mathrm{UL}} = \lambda_{\mathrm{DL}} = 0.5$) to moderate ($\lambda_{\mathrm{UL}} = \lambda_{\mathrm{DL}} = 1.5$) packet arrival rate are considered.

4.2 Simulation results

In order to verify the effectiveness of the proposed shifting-based dynamic TDD (S-TDD) scheme, the

Table 1 Simulation parameters

Name	Value
Simulation scenario	2 clusters/macro cell; 4 small cells/cluster
Inter-site distance	30 m
Carrier frequency	3.5 GHz
Bandwidth	10 MHz
Channel model	ITU M.2135 UMi
Transmit power	24 dBm
Scheduling strategy	Proportional fairness (PF)
UE number	2 UE/macro cell
Antenna pattern	Omni-directional
Antenna height	Base station, 6 m UE, 1.5 m
Antenna gain plus connection loss	5 dBi
UE movement speed	3 km/h
Service type	FTP model 1: $\lambda_{\mathrm{UL}} = \lambda_{\mathrm{DL}} = 0.5$ (low arrival rate); $\lambda_{\mathrm{UL}} = \lambda_{\mathrm{DL}} = 1.5$ (moderate arrival rate)
Reconfiguration cycle	40 ms
Worst SINR threshold (S-TDD)	0 dB

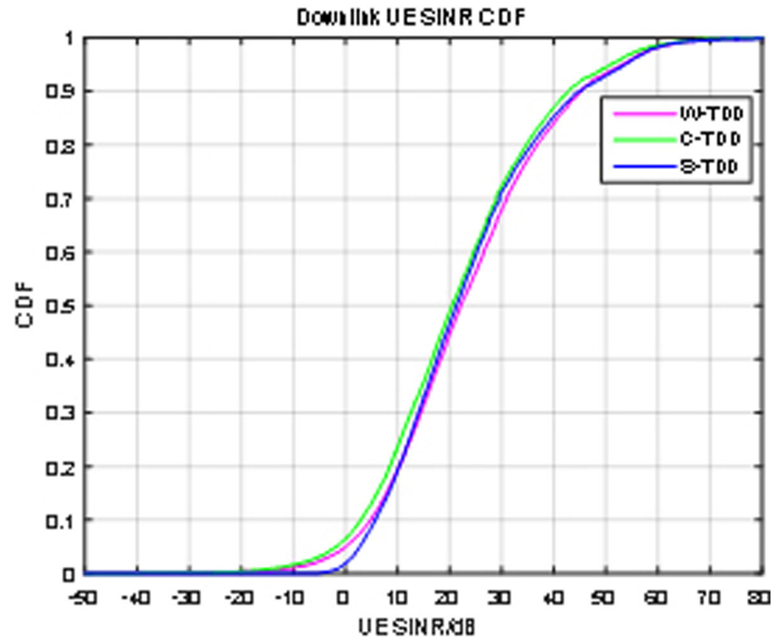

Fig. 5 UE downlink SINR

performance is compared with that of W-TDD algorithm [22] and C-TDD algorithm [21].

In the case of moderate packet arrival rate, the downlink and uplink SINR results are shown in Figs. 5 and 6, respectively. It can be seen that the downlink SINR performance of C-TDD algorithm is a little worse than that of W-TDD algorithm; however, the uplink SINR performance is better than that of W-TDD algorithm. The reason is that W-TDD algorithm may cause a lot of cross-slot interference and C-TDD algorithm can eliminate this kind of interference while keeping traditional interference. The simulation results show that the C-TDD method can improve the uplink SINR performance at the expense of a slight deterioration of the downlink SINR and therefore improves the overall system performance.

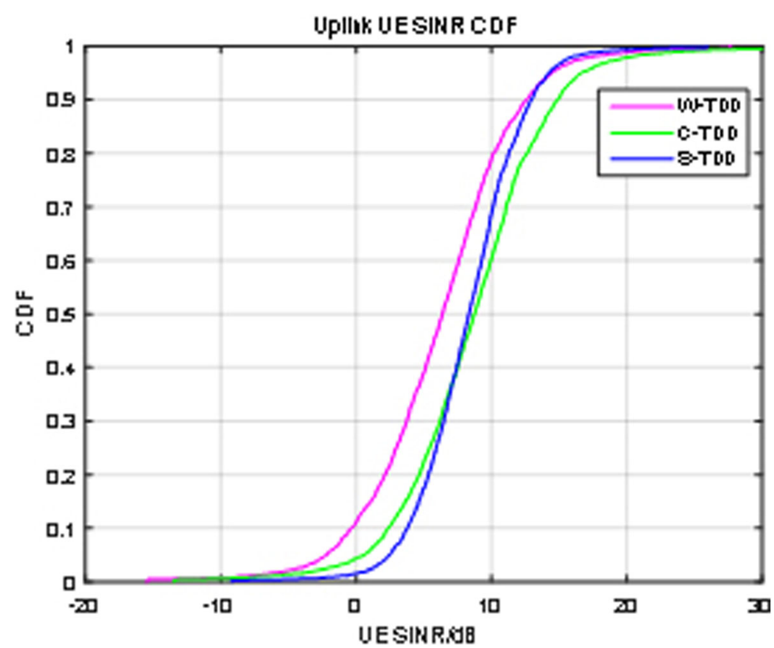

Fig. 6 UE uplink SINR

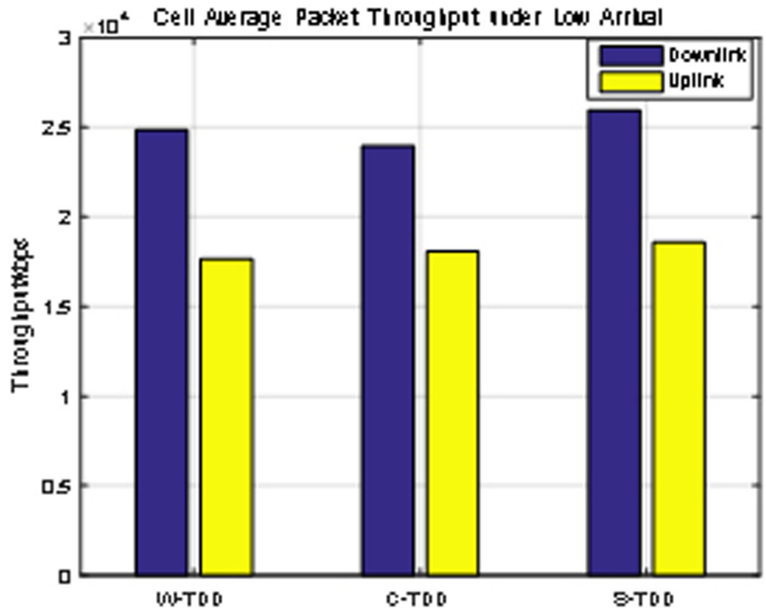

Fig. 7 Average packet throughput at low packet arrival rates

The proposed S-TDD algorithm preserves partial cross-slot interference and traditional interference, and the SINR performance lies between that of W-TDD algorithm and that of C-TDD algorithm. The S-TDD method sets the worst SINR threshold to 0, because the SINR of almost all users is greater than 0 and it can ensure the fairness among the UEs and avoid the emergence of poor wireless links.

Figure 7 shows the average packet throughput in the case of low packet arrival rate ($\lambda_{UL} = \lambda_{DL} = 0.5$), and Fig. 8 shows the average packet throughput in the case of moderate packet arrival rate ($\lambda_{UL} = \lambda_{DL} = 1.5$). It can be seen that the C-TDD method has a relatively low downlink average packet throughput comparing with the W-TDD method while the average uplink packet throughput performance is improved. There are two factors that limit the packet throughput: SINR and to what degree the TDD configuration is compliant to the traffic requirements. Too low SINR will lead to poor channel capacity, which will limit the upper bound of the packet

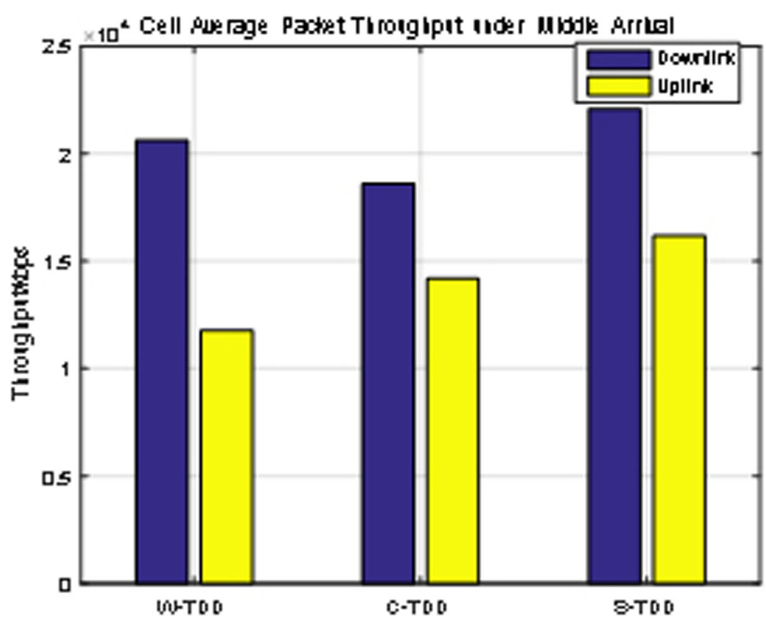

Fig. 8 Average packet throughput at moderate packet arrival rates

throughput. The mismatch between the TDD configuration and the traffic requirements will result in a redundant resource in downlink/uplink direction and a lack of resources in the other. As can be seen from Fig. 7, due to the low packet arrival rate and high SINR, the throughput improvement by C-TDD method cannot compensate for the throughput reduction due to matching between TDD configuration and the traffic. In Fig. 8, due to moderate packet arrival rate and low SINR, the SINR becomes the main factor that limit the system throughput, and the throughput gain by cell clustering is higher than the throughput loss by non-ideal TDD configuration. Therefore, it is necessary to use the W-TDD method when the load is low, while it is necessary to adopt C-TDD method to resist the interference.

5 Conclusions

This paper presents a dynamic TDD algorithm that considers both traffic and interference factors to guarantee system performance. The proposed dynamic TDD method shows better performance on the aspect of uplink and downlink throughput in cases of low to moderate load comparing with that of W-TDD method and C-TDD method. Furthermore, the proposed method will turn into W-TDD method or C-TDD method in conditions of low SINR or high SINR, respectively. The proposed dynamic TDD method can avoid the occurrence of wireless communication links with too low SINR, which ensures high average packet throughput.

Funding

This work is supported by Major National Scientific & Technological Specific Project of China under grant number 2016ZX03001009-003.

Authors' contributions

WG conceived and designed the study. BL performed the experiments. GC reviewed and edited the manuscript. All authors read and approved the manuscript.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

Received: 4 April 2017 Accepted: 5 May 2017
Published online: 16 May 2017

References

1. B Li, SH Li, A Nallanathan, CL Zhao, Deep sensing for future spectrum and location awareness 5G communications. IEEE Journal Selected Areas Communications **33**(7), 1331–1344 (2015)
2. B Li, Z Zhou, WX Zou, XB Sun, GL Du, On the efficient beam-forming training for 60 GHz wireless personal area networks. IEEE Trans. Wireless Commun. **12**(2), 504–515 (2013)
3. B Li, Z Zhou, ZHJ Zhang, A Nallanathan, Efficient beamforming training for 60-GHz millimeter-wave communications: a novel numerical optimization framework. IEEE Transactions on Vehicular Technology **63**(2), 703–717 (2014)
4. 3GPP TR 36.932, *Scenarios and requirements for small cell enhancements for E-UTRA and E-UTRAN (Release 12), v12.1.0*, 2013
5. Y Wang, M Tao, *Dynamic uplink/downlink configuration using Q-learning in femtocell networks*. 2014 IEEE/CIC International Conference on Communications in China (ICCC), Shanghai, 2014, pp. 53–58
6. H Sun, M Sheng, M Wildemeersch, TQS Quek, *Coverage analysis for two-tier dynamic TDD heterogeneous networks*. 2014 IEEE Global Communications Conference, Austin, TX, 2014, pp. 3672–3677
7. Y Gao, L Cheng, Y Li, X Zhang, D Yang, *Performance evaluation on cell clustering interference mitigation and CoMP in multi-pico network with dynamic TDD*. 2015 IEEE 81st Vehicular Technology Conference (VTC Spring), Glasgow, 2015, pp. 1–5
8. M Ding, D López-Pérez, AV Vasilakos, W Chen, *Analysis on the SINR performance of dynamic TDD in homogeneous small cell networks*. 2014 IEEE Global Communications Conference, Austin, TX, 2014, pp. 1552–1558
9. A Khoryaev, A Chervyakov, M Shilov, S Panteleev, A Lomayev, *Performance analysis of dynamic adjustment of TDD uplink-downlink configurations in outdoor picocell LTE networks*. 2012 IV International Congress on Ultra Modern Telecommunications and Control Systems, St. Petersburg, 2012, pp. 914–921
10. H Sun, M Wildemeersch, M Sheng, TQS Quek, D2D enhanced heterogeneous cellular networks with dynamic TDD. IEEE Transactions on Wireless Communications **14**(8), 4204–4218 (2015)
11. Y Li, Z Lin, H Liu, Y Gao, X Zhang, X Liu, *Performance evaluation of a resource allocation scheme for mixed traffic in dynamic-TDD network*. 2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall), Vancouver, BC, 2014, pp. 1–5
12. K Nguyen, L Zappaterra, HA Choi, *A centralized algorithm for dynamic TDD frame reconfigurations in synchronized HetNets*. 2015 IEEE International Conference on Communication Workshop (ICCW), London, 2015, pp. 113–118
13. MS ElBamby, M Bennis, W Saad, M Latva-aho, *Dynamic uplink-downlink optimization in TDD-based small cell networks*. 2014 11th International Symposium on Wireless Communications Systems (ISWCS), Barcelona, 2014, pp. 939–944
14. M Tao, Q Cui, X Tao, H Xiao, *Realtime dynamic clustering for interference and traffic adaptation in wireless TDD system*. 2014 IEEE Symposium on Computational Intelligence in Production and Logistics Systems (CIPLS), Orlando, FL, 2014, pp. 128–133
15. AM Fouladgar, O Simeone, O Sahin, P Popovski, S Shamai, *Joint interference alignment and bi-directional scheduling for MIMO two-way multi-link networks*. 2015 IEEE International Conference on Communications (ICC), London, 2015, pp. 4126–4131
16. CC Chao, CH Lee, HY Wei, CY Wang, WT Chen, *Distributed dynamic-TDD resource allocation in femtocell networks using evolutionary game*. 2015 IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Hong Kong, 2015, pp. 1157–1162
17. F Sun, Y Zhao, *Cell cluster-based dynamic TDD DL/UL reconfiguration in TD-LTE systems*. 2016 IEEE Wireless Communications and Networking Conference, Doha, 2016, pp. 1–5
18. D Della Penda, L Fu, M Johansson, Energy efficient D2D communications in dynamic TDD systems. IEEE Transactions on Communications **65**(3), 1260–1273 (2017)
19. A Lukowa, V Venkatasubramanian, *Performance of strong interference cancellation in flexible UL/DL TDD systems using coordinated muting, scheduling and rate allocation*. 2016 IEEE Wireless Communications and Networking Conference, Doha, 2016, pp. 1–7
20. F Sanchez Moya, V Venkatasubramanian, P Marsch, A Yaver, *D2D mode selection and resource allocation with flexible UL/DL TDD for 5G deployments*. 2015 IEEE International Conference on Communication Workshop (ICCW), London, 2015, pp. 657–663
21. J Liu, S Han, W Liu, *Performance gain of full duplex over half duplex under bidirectional traffic asymmetry*. 2016 IEEE International Conference on Communications Workshops (ICC), Kuala Lumpur, 2016, pp. 98–103
22. P Popovski, O Simeone, JJ Nielsen, Č Stefanović, Interference spins: scheduling of multiple interfering two-way wireless links. IEEE Communications Letters **19**(3), 387–390 (2015)
23. M Tao, Q Cui, Y Hong, C Yin, H Liang, *Max K-CUT based clustering for interference mitigation and traffic adaptation in TDD systems*. 2014 IEEE 79th Vehicular Technology Conference (VTC Spring), Seoul, 2014, pp. 1–5
24. L Xue, Y Cheng, Y Zhou, B Qu, *Next generation TDD cellular communication*. 2015 49th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, 2015, pp. 1036–1040