Coordinated Downlink/Uplink Transmission Assignment and Dynamic Switching in Hybrid TDD System

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***Abstract*—Dynamic Time Division Duplex (TDD) or flexible TDD, one of the key technology of 5G-New Radio (NR), can improve the system performance obviously. The base stations (BS) can change downlink and uplink transmission directions flexibly at the beginning of the frame. There are hetrogeneous interference sources in a dynamic TDD system, such as crosslink interference (CLI), which is caused by simultaneous downlink and uplink transmissions. One type of CLI, BS-to-BS interference, degrades the performance of uplink transmission seriously. To mitigate the BS-to-BS interference and keep flexible duplex working efficiently, this study proposes a hybrid TDD system with the premeasured algorithm. The hybrid system combines the feature of static TDD and dynamic one and can mitigate CLI and keep transmission flexible. To transmit with variable traffic load, the premeasured algorithm takes the buffer status of each transmitter into account. Through the system-level simulation, it is verified that the proposed hybrid TDD system with premeasured algorithm can decrease effect of BS-to-BS interference and provide higher spectral efficiency than dynamic TDD does without any CLI mitigation.**

***Keywords*—5G-NR, hybrid TDD, flexible duplex, CLI, system-level simulation**

I. Introduction

Unpaired spectrum allocations are increasingly common in high frequency band, and time division duplex (TDD) systems often operate in these spectrum allocations due to flexibility. However, Long Term Evolution (LTE) supports only static TDD, where the TDD uplink-downlink allocation does not change over time. [1] In such a static TDD system, all base stations (BSs) and user equipments (UEs) operate in the same TDD configuration, which means interference sources are homogeneous. Interference of downlink transmissions comes from other downlink transmissions, and vice versa for uplink transmissions. In 5G-NR system, [2] since the dense deployment of the cells, the per-cell traffic variations are more rapid. To address such variable traffic, dynamic TDD, a key technology of NR, dynamically assigns and reassigns the time-domain resources between the downlink and uplink transmission directions.

However, dynamic TDD is not a perfect solution, compared to static TDD. Interference situations of dynamic TDD are more complicated. Interferences of dynamic TDD consist of BS-to-UE interference, UE-to-BS interference, and crosslink interference (CLI), as shown in Fig. 1. CLI, the main problem in dynamic TDD, is incurred by downlink (DL) and uplink (UL) transmissions at the same time. Furthermore, CLI seriously effects on the cell UL UEs, and makes their SINR dramatically degrade. To decrease the effect of CLI, there are many researches about CLI mitigation schemes.

Reference [3] mentioned that there are several methods to mitigate CLI, for example, power control, scheduling coordination, and hybrid dynamic/static UL/DL resource assignment (hybrid TDD). Power control mainly decreases BS transmission power to mitigate BS-to-BS interference. Scheduling coordination uses scheduling scheme to avoid serious CLI. Hybrid TDD mainly focuses on changing frame format to mitigate CLI. Hao et al. [4] restrict the transmit power of aggressor BSs to mitigate the BS-to-BS interference according to signal-to-interference-plus-noise ratio (SINR) of UL victim BSs. Tang et al. [5] not only restrict the transmit power of aggressor BSs but also combine beam coordination. Lee et al. [6] propose a hybrid TDD scheme to mitigate CLI effect on cell edge UEs, considering SINR and beam angle to recognize whether the UE is at cell edge or cell center. Cell edge UEs use static slots in the frame format of hybrid TDD and cell center UEs use dynamic slots. Above works mainly focus on the value of SINR, but few works focus on buffer status. Although reference [7] is not working for CLI mitigation, this paper proposes the coordination of multiple BSs which is rare for the research about CLI mitigation. To fully mitigate the effect of CLI and flexibly use resources, this study proposes the hybrid TDD with premeasured algorithm, which considers buffer status and coordinates multiple BSs at the same time.

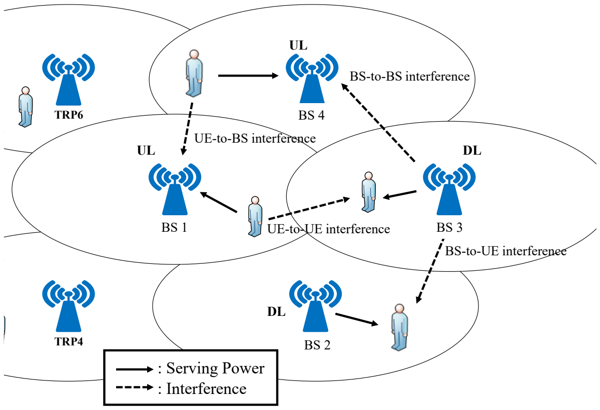

Fig. 1. Dynamic TDD interference scenario

II. System Model and Problem Formulation

A. CLI Scenario

We consider the multi-BS dynamic TDD system with wrapping around, in which the slot configuration changes dynamically in each BS. The CLI is caused by simultaneous transmission of DL and UL. There are two kinds of CLI: BS-to-BS interference and UE-to-UE interference. As shown in Fig. 1, BS-to-BS interference or DL-to-UL interference is the DL signal interfering UL signal reception. UE-to-UE interference or UL-to-DL interference is the case that the UL signal interferes reception of the DL signal.

B. Semi-static TDD Frame Format

The proposed Hybrid TDD is based on semi-static TDD in [8]. There are two modes in the frame format of semi-static: fixed slot and flexible slot. Fixed slots, similar to static TDD, are defined as slots where every BS and UE transmit in the same direction (DL/UL). In flexible slots, similar to dynamic TDD, each BS decides its own direction (DL/UL). Since BS does not know the direction of adjacent BS, the CLI in flexible slot may be serious.

C. Packet Throughput and Packet Delay

Considering a multi-BS hybrid TDD system, we define the BSs as $\mathbf{N} = \{1,2,\dots,N\}$, and the UEs in the n-th BS as $\mathbf{U}_n = \{1_n, 2_n, \dots, U_n\}$, where $n \in \mathbf{N}$. The received DL packets and sent UL packets of the u_n-th UE are defined as $\mathbf{P}^D_{u_n} = \{1^D_{u_n}, 2^D_{u_n}, \dots, P^D_{u_n}\}$ and $\mathbf{P}^U_{u_n} = \{1^U_{u_n}, 2^U_{u_n}, \dots, P^U_{u_n}\}$, respectively. The single DL packet throughput $TP_{p^D_{u_n}}$ of $p^D_{u_n}$-th DL packet in u_n-th UE in BS n is denoted as

$$TP_{p^D_{u_n}} = \frac{s_{p^D_{u_n}}}{d_{p^D_{u_n}}} \tag{1}$$

where $p^D_{u_n} \in \mathbf{P}^D_{u_n}$, $s^D_{p_{u_n}}$ is the DL packet size of packet $p^D_{u_n}$, and $d_{p^D_{u_n}}$ is the DL packet delay of packet $p^D_{u_n}$. Fig. 2 illustrates an example of the packet delay, which is defined as the time interval between the generation of a packet and the successful reception of the final block (before sending the final acknowledgement for that), where we assume that a packet is divided into three transport blocks in this example. After receiving the single DL packet throughput, we can calculate the average UE DL packet throughput TP^D and delay d^D from (1):

$$TP^D = \sum_{n\in\mathbf{N}} \left(\frac{\sum_{u_n\in\mathbf{U}_n} \sum_{p^D_{u_n}\in\mathbf{P}^D_{u_n}} TP_{p^D_{u_n}}}{\sum_{u_n\in\mathbf{U}_n} \left|\mathbf{P}^D_{u_n}\right|} \right) \Big/ |\mathbf{N}| \tag{2}$$

$$d^D = \sum_{n\in\mathbf{N}} \left(\frac{\sum_{u_n\in\mathbf{U}_n} \sum_{p^D_{u_n}\in\mathbf{P}^D_{u_n}} d_{p^D_{u_n}}}{\sum_{u_n\in\mathbf{U}_n} \left|\mathbf{P}^D_{u_n}\right|} \right) \Big/ |\mathbf{N}| \tag{3}$$

Note that the average UE UL packet throughput TP^U and delay d^U are the same as DL's by turning all D to U in (1)-(3).

D. Spectral Efficiency

To evaluate the system performance, we compare the average spectral efficiency and the cell edge UE spectral efficiency between static TDD, dynamic TDD, and the proposed hybrid TDD. Spectral efficiency, one of the important indicators of simulation results, is usually used to evaluate the system performance, and well defined in [9]. The average DL spectral efficiency SE^D_{avg} is the average spectral efficiency of BSs which is defined as

$$SE^D_{avg} = \frac{\sum_{n\in\mathbf{N}} \left(\sum_{u_n\in\mathbf{U}_n} \left(R^D_{u_n}\right) \Big/ T^D_n \times W \right)}{|\mathbf{N}|} \tag{4}$$

where $R^D_{u_n}$ is the total received bits by user (DL) in BS n, W is bandwidth, and T^D_n is the total time that BS n spends for DL transmission. The cell edge UE spectral is defined as the 5-th percentile of the cumulative distribution function (CDF) of the user spectral efficiency. The DL user spectral efficiency $SE^D_{u_n}$ is defined as

$$SE^D_{u_n} = \frac{R^D_{u_n}}{T^D_{u_n} \times W} \tag{5}$$

where $T^D_{u_n}$ is the total time that UE u_n spends for DL transmission. Note that the average UL spectral efficiency SE^U_{avg} and the UL user spectral efficiency $SE^U_{u_n}$ are the same as DL's.

III. Proposed Schemes

The main spirit of the proposed hybrid TDD with premeasured algorithm is efficiently decreasing the BS-to-BS interference and flexibly fitting offered traffic simultaneously. The static TDD system can't bear the variable traffic scenario. In dynamic TDD system, many UEs suffer BS-to-BS interference and transmit inefficiently. To solve the problem of the static TDD and the dynamic TDD, we combine the hybrid TDD and the proposed premeasured algorithm. The premeasured algorithm controls the number of the DL BS nearby the UL BSs, and the hybrid TDD provides flexible duplexing.

A. Hybrid TDD Frame Format

The proposed Hybrid TDD chooses the 4G-LTE TDD frame format configuration 1 and changes some slot into flexible slot (F). In Fig. 3, the static slots use static TDD (TDD configuration 1), and the flexible slots can use either static TDD or dynamic TDD. The final direction of flexible slot is decided by the proposed premeasured algorithm.

B. Central Control Units

The main function of Central Control Units (CCUs) is to coordinate direction of each base station/site in a centralized management manner. CCUs collect the information from BSs and use proposed algorithm to coordinate the DL/UL allocation of each site (three BSs or namely cells per site, with always the same transmission direction). Each CCU is responsible for a collection of nearby sites, and every sites belongs to only one CCU. We assume 19 sites and one CCU in the simulation environment. There are time delay between the BSs send the buffer status message to the CCUs and receive the direction information from the CCUs. The delay is about 20ms when CCUs and BS connect with wired communication system[10], and is about 8 ms when CCUs and BS connect with wireless communication system[11]. This study uses wired communication system to connect CCUs and BSs so the delay is about 20 ms.

C. Proposed Premeasured Algorithm

Before introducing the method in detail, this study divides the method into three phases: Phase 1) Each site collects the buffer status and sends to the CCUs at the beginning of the frame; Phase 2) CCUs receive the buffer status from sites and evaluate the transmission direction of each site by premeasured algorithm; Phase 3) CCUs send direction information to the sites.

In phase 1, each BS needs to know how many packets are queued in the served UEs. For the UL direction, each UE sends buffer status report (BSR) to the serving BS and makes the BS know how many packets are waiting for sending. On the other hand, the BS knows the buffer status in the DL transmission by itself. After learning of the buffer status about DL and UL, the BS will send the information to the CCUs.

In phases 2 and 3, the CCUs determine whether the sites are DL sites or UL sites by their own buffer status. If the DL buffer size is larger than the UL buffer size the site shall be in DL transmission, and vice versa. Then, CCUs count the total number of DL sites and UL sites. If the number of DL sites is larger than that of UL sites, CCUs invoke these sites operating in static TDD mode; otherwise, CCUs tell each site operating in its own direction depending on which direction of traffic is dominant.

Thus, the command from the CCU to each site can be three cases: 1) Static, all sites transmitting in static TDD mode (assuming TDD configuration 1 in the simulation), 2) UL direction, in the case the sites turn all of the flexible slots into UL, and 3) DL direction, in the case the sites turn all of the flexible slots into DL.

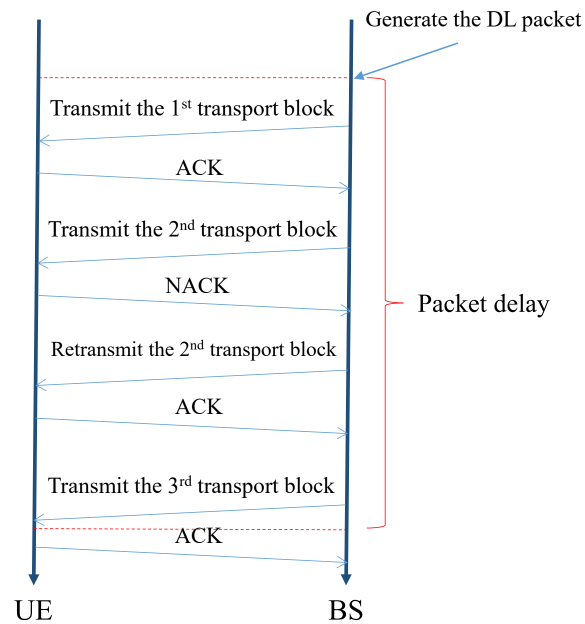

Fig. 2. Illustration for the packet delay

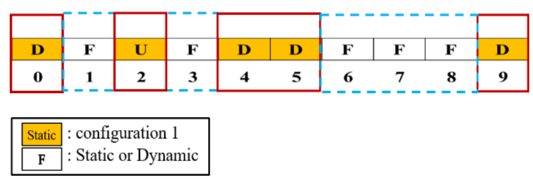

Fig. 3. Illustration for the frame structure for the proposed hybrid TDD system

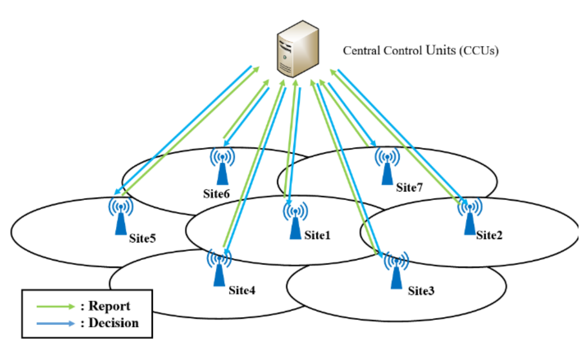

Fig. 4. Illustration for CCUs

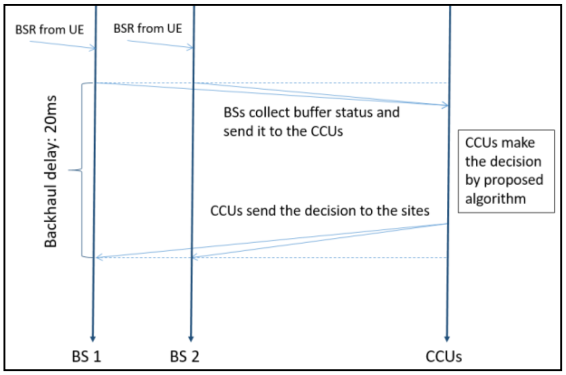

Fig. 5. Message Flow Diagram of CCUs and BSs

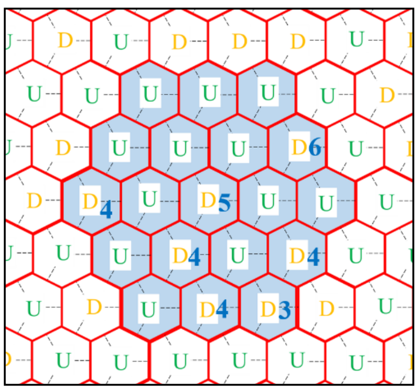

Fig. 6. Illustration for the method of converting DL sites to UL sites with warpping around of blue region

To further decrease the BS-to-BS interference this study proposes to decrease the number of DL site nearby the UL site, denoted by the number *u*. Before the CCUs reporting the direction information, the algorithm converts *u* DL sites to UL sites. Then, the CCUs send the direction information (include converted sites) to the sites. The converting order is according to the number of UL sites nearby the DL sites, as shown in Fig. 6. For example, the number six is the first converted, and the number five is the second, until converting the largest *u* DL sites to UL sites. In the case of that the numbers of nearby UL sites for two DL sites are equal, the DL site with the larger UL buffer size is converted first, which can decrease its UL queueing delay.

IV. Simulation Results

To evaluate the performance of the proposed hybrid TDD with premeasured algorithm, we simulate an outdoor scenario in the WiSE simulator [12,13] and employ the parameters summarized in Table 1. We assume that the scenario contains 19 sites and 57 BSs. The traffic model of DL and UL is FTP model 1 in 3GPP TR 36.814 [14] with the same load and the scheduler in each BS implements the round robin algorithm.

Because the DL transmission power is much larger than UL transmission power, the power of UE-to-UE interference is usually less than that of BS-to-UE interference, and the power of BS-to-BS interference is larger than that of UE-to-BS interference. That's why the dynamic TDD scheme performs better than the static TDD does in the viewpoint of DL SINR but performs opposite in UL SINR, as shown in Fig. 7 and Fig. 8. Both in the Fig. 7 and 8 of UL and DL SINR, the curve of hybrid TDD with u=0 is almost the same as the curve of hybrid TDD with u=3, which means that over restricting the number of DL sites can't benefit the system. Fig. 8 shows that the proposed hybrid TDD performs not only better than the dynamic TDD scheme does but also almost as well as the static TDD scheme does. The resource utilization is the percentage of time that BS uses DL or UL transmission. As shown in Table 2 and Table 3, using higher resource utilization can improve the UE average packet delay and the average UE packet throughput.

Although the dynamic TDD system performs well in DL SINR and dynamic TDD can address to the variable traffic, the cell edge UEs have tragic UL SINR. Due to the tragic SINR of the cell edge UL UEs, the UE outage rate must be high. The propose hybrid TDD not only address to the variable traffic but also perform better than dynamic TDD on UL SINR which cause lower UL UE outage rate. As shown in Table 4, when the DL-to-UL traffic ratio increases, the dynamic TDD's SINR obviously decreases; on the other hand, the proposed hybrid TDD's SINR only slightly decreases in this situation.

TABLE I. Simulation Parameters

Parameters	Value
Carrier frequency	4 GHz
Inter-site distance	500 m
BS antenna height	25 m
UE antenna height	1.5 m
System bandwidth	10 MHz
Max transmit power	BS: 46 dBm
	UE: 23 dBm
Percentage of high loss and low loss building type	100% low loss
BS antenna elements	(M. N, P, Mg, Ng)=(8,2,2,1,1) (dH, dv)=(0.5, 0.8)λ
UE antenna elements	(M. N, P, Mg, Ng)=(1,2,2,1,1) (dH, dv)=(0.5, N/A)λ
UE distribution	10 UEs per BS 20% indoor and 80% outdoor
UE speed	Indoor users: 3 km/h Outdoor users: 30 km/h
BS noise figure	5 dB
UE noise figure	7 dB
Traffic model	FTP model 1, Packet size 0.5Mbytes Downlink 0.4 arrivals/sec/UE Uplink 0.4 (0.2) arrivals/sec/UE
Max layer number	1
MCS	Max to 256QAM
Channel model	Channel model B
Channel estimation	Ideal

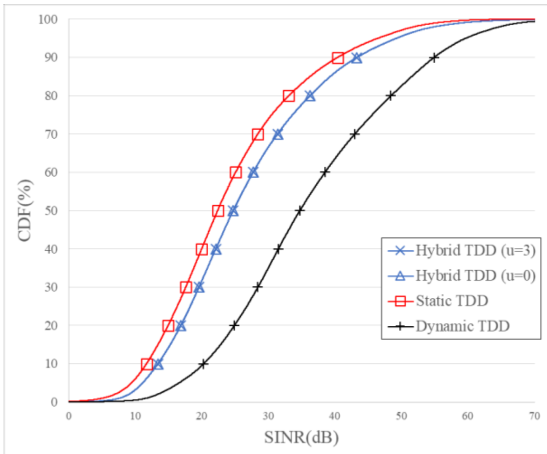

Fig. 7. DL SINR under different TDD schemes

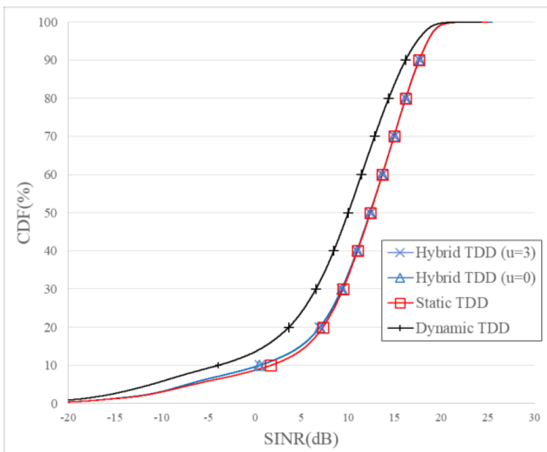

Fig. 8. UL SINR under different TDD schemes

Moreover, the proposed hybrid TDD uses the resource more efficient. As shown in Table 2 and Fig. 8, the dynamic TDD system spends lots of the resource on UL transmission, but the UL transmission quality is poor. Due to the proposed hybrid TDD, the transmission quality of UL transmission increase and the system does not spend lots of resource on the poor transmission quality.

The proposed hybrid TDD with premeasured algorithm takes both traffic and interference into account and suppresses the CLI, especially BS-to-BS interference. In the UL transmission, high resource utilization makes dynamic TDD have low packet delay but the quality of transmission is poor. Hybrid TDD offers the high quality transmission, the average UL cell spectral efficiency is 45.8% higher than that of dynamic TDD.

Through this work we can learn the relationships between the simulation parameters and results. As shown in Fig. 9, SINR influences the error rate and MCS. When SINR grows up, the error rate may decrease and BSs can choose higher MCS. Choosing the higher MCS can let BSs and UEs transmit more data, which increases the spectral efficiency and decreases the packet delay. Although resource utilization and packet size influence packet delay, they don't affect the spectral efficiency. The spectral efficiency depends on the whole system rather than a single packet.

V. Conclusions

This study mainly works on the hybrid TDD, and proposes the premeasured algorithm and CCUs. According to the buffer status, CCUs switch the TDD mode and mitigate the BS-to-BS interference. The UL spectral efficiency increases due to decreased BS-to-BS interference. For the UL transmission, the proposed hybrid TDD with premeasured algorithm is not only fitting to traffic but also efficient in radio spectrum. In the future, we will study the performance in indoor scenario and make hybrid TDD transmit more efficiently.

TABLE II. DL Simulation Result under different TDD schemes

Table Head	Schemes		
	Static	***Dynamic***	***Hybrid (u=0)***
Resource Utilization (%)	54.9899	28.1029	41.3873
Cell Edge UE Spectral Efficiency (bps/Hz)	1.0809	2.2230	1.4415
Average Spectral Efficiency (bps/Hz)	2.7340	3.8735	3.1602
UE Average Packet Delay (Sec)	1.6284	3.3831	2.1818
Average UE Packet Throughput (Mbps)	5.1925	2.2883	3.2199

TABLE III. UL Simulation Result under Different TDD Schemes

Table Head	Schemes		
	Static	***Dynamic***	***Hybrid (u=0)***
Resorce Utilization (%)	39.4053	69.9343	56.2242
Cell Edge UE Spectral Efficiency (bps/Hz)	0.1695	0.1437	0.1812
Average Spectral Efficiency (bps/Hz)	3.7913	1.5987	2.3324
UE Average Packet Delay (Sec)	4.9725	2.8991	3.1844
Average UE Packet Throughput (Mbps)	1.6919	2.7770	2.1723

TABLE IV. UL SINR Under Different Packet Arrival Rate

Table Head	Schemes			
	Uplink 0.4 arrivals/sec/UE (DL:UL=1:1)		**Uplink 0.2 arrivals/sec/UE (DL:UL=2:1)**	
	Dynamic	***Hybrid***	***Dynamic***	***Hybrid***
5-percentile	-11.0912	-7.29029	-12.6504	-7.12824
50-percentile	10.0008	12.3396	7.52173	11.4218
95-percentile	17.3877	18.5354	15.4249	18.3434

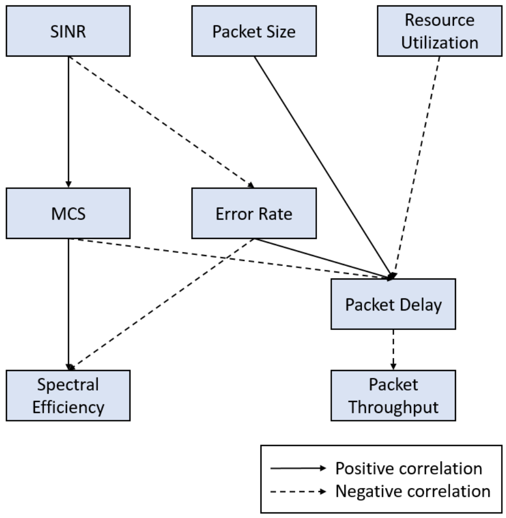

Fig. 9. Relationships between simulation parameters and results

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