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Ksairi et al.

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(45) **Date of Patent: Aug. 19, 2025**

(54) **TRANSMITTER DEVICE AND RECEIVER DEVICE FOR A WIRELESS COMMUNICATION SYSTEM**

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(73) Assignee: **Huawei Technologies Co., Ltd.**, Shenzhen (CN)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 56 days.

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(22) Filed: **Aug. 24, 2023**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
H04L 27/26 (2006.01)
H04B 7/0452 (2017.01)

(52) **U.S. Cl.**
CPC ***H04L 27/2639*** (2013.01); ***H04B 7/0452*** (2013.01); ***H04L 27/2607*** (2013.01)

(58) **Field of Classification Search**
CPC H04L 27/2639; H04L 27/2607; H04B 7/0452
See application file for complete search history.

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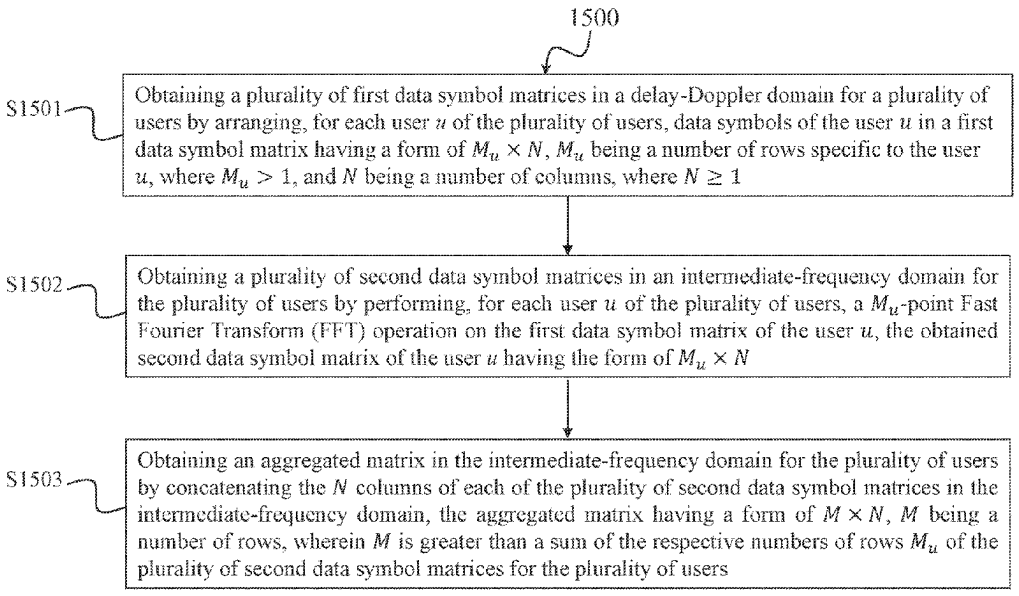
Primary Examiner — David S Huang
(74) *Attorney, Agent, or Firm* — Leydig, Voit & Mayer, Ltd.

(57) **ABSTRACT**

The present disclosure relates to a transmitter device and a receiver device for a wireless communication system supporting low-overhead multiple access for a layered Fast Fourier Transform-based wireless communication. The transmitter device obtains a plurality of first data symbol matrices in a delay-Doppler domain for a plurality of users, a plurality of second data symbol matrices in an intermediate-frequency domain for the plurality of users, and an aggregated matrix in the intermediate-frequency domain for the plurality of users. The receiver device obtains an aggregated matrix in the intermediate-frequency domain for a plurality of users based on a signal received in a time domain from the transmitter device, a plurality of first data symbol matrices in the intermediate-frequency domain for the plurality of users, and a plurality of second data symbol matrices in the delay-Doppler domain for the plurality of users.

19 Claims, 25 Drawing Sheets



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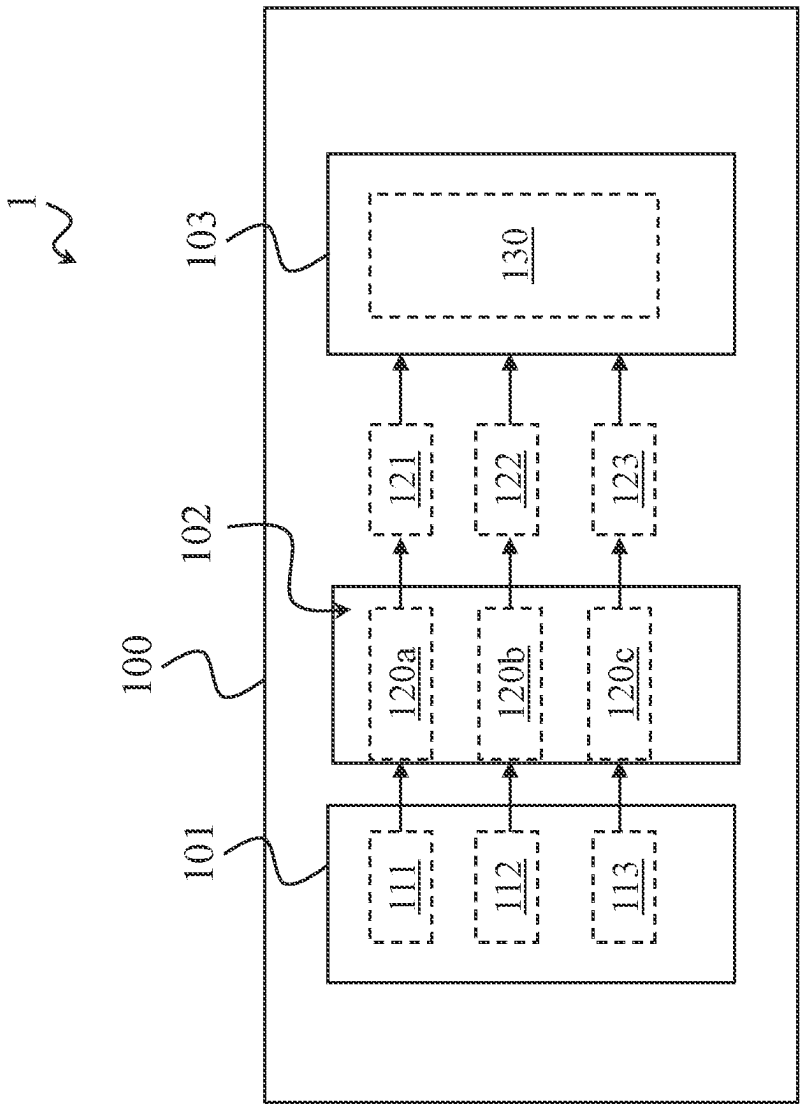

FIG. 1

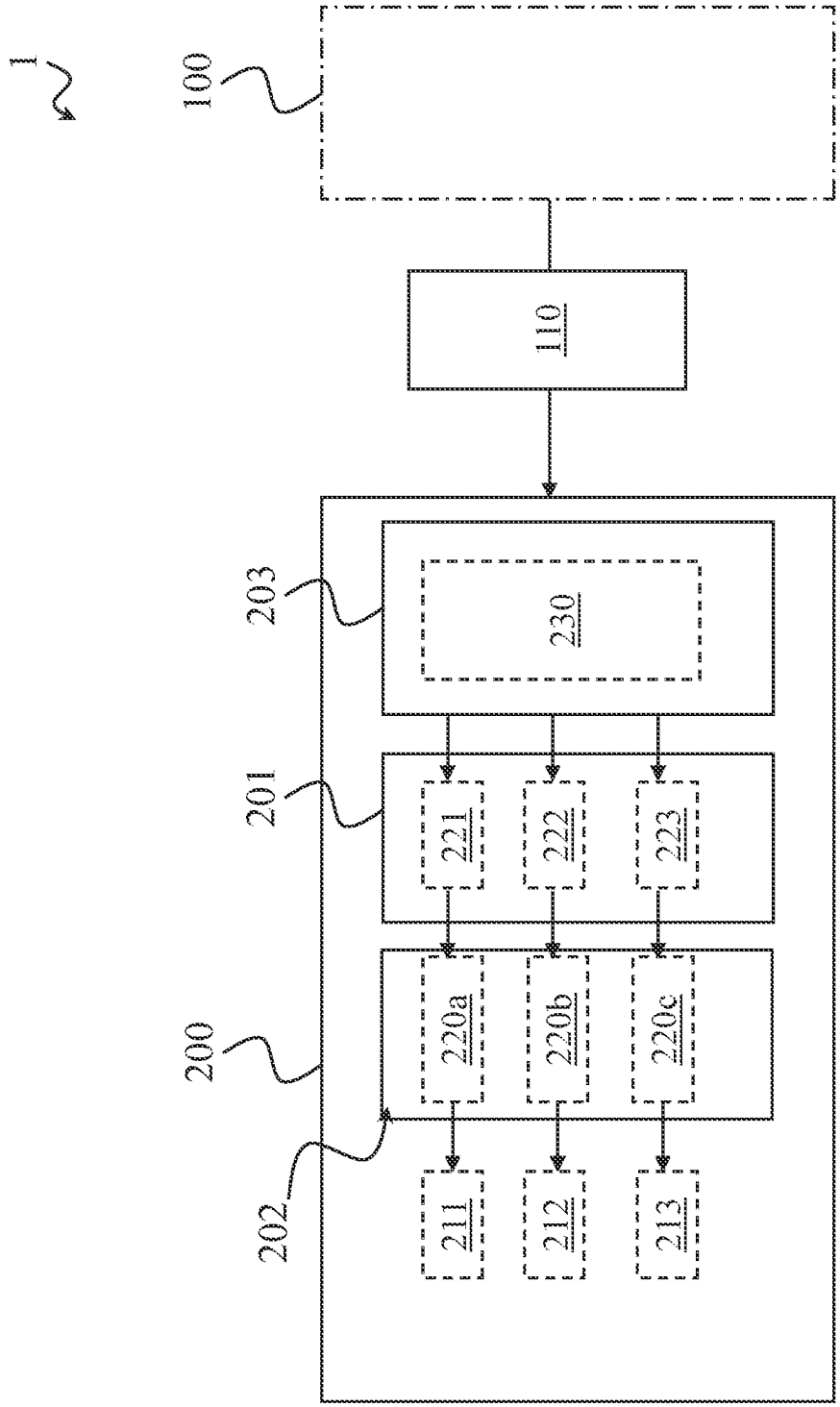
1
100
110
203
230
201
221
222
223
200
220a
220b
220c
202
211
212
213

FIG. 2

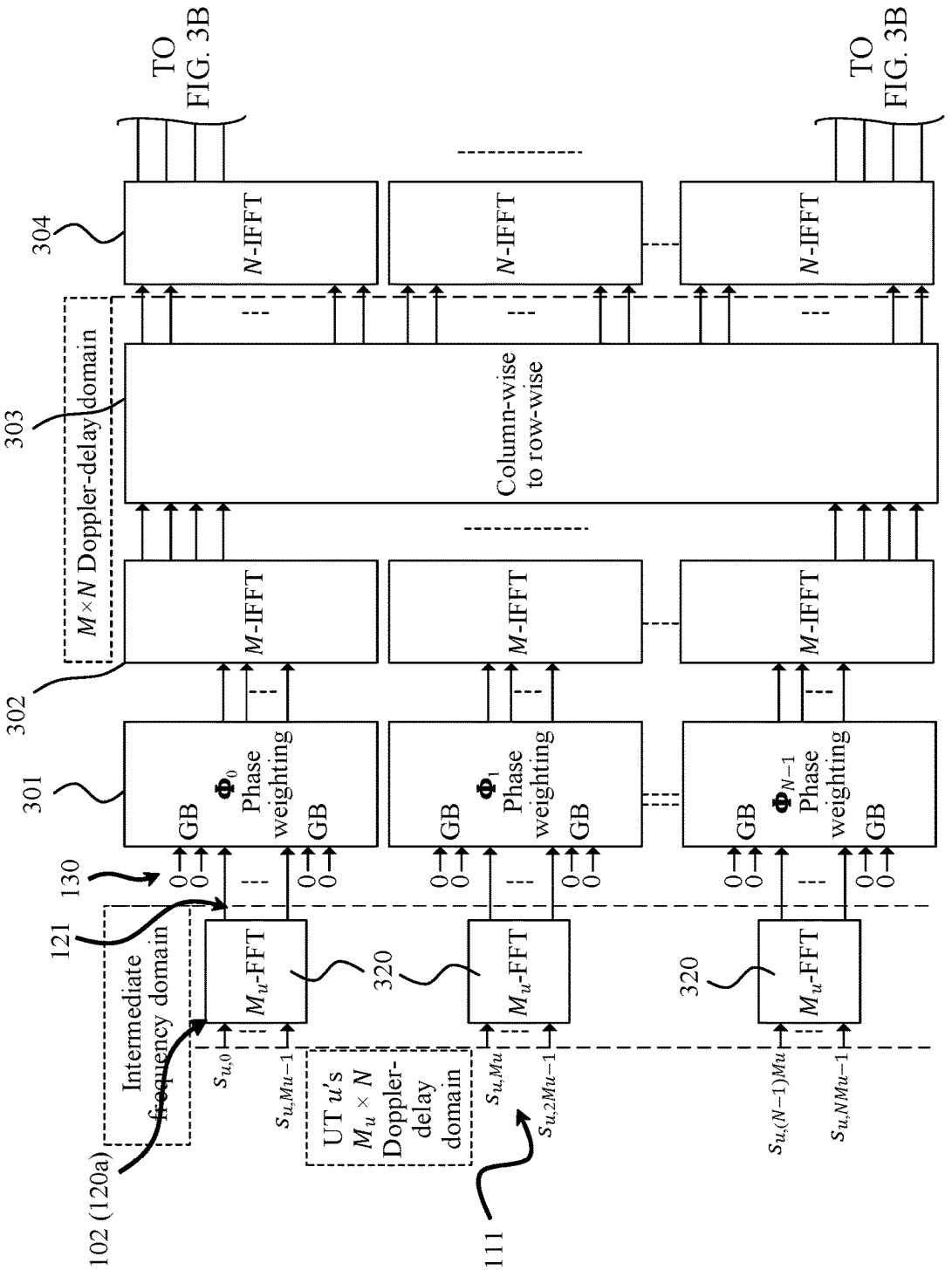
TO FIG. 3B
TO FIG. 3B
304
N-IFFT
N-IFFT
N-IFFT
303
M×N Doppler-delay domain
Column-wise to row-wise
302
M-IFFT
M-IFFT
M-IFFT
301
GB
Φ0 Phase weighting
GB
GB
Φ1 Phase weighting
GB
GB
ΦN−1 Phase weighting
GB
130
121
Intermediate frequency domain
Mu-FFT
320
Mu-FFT
320
Mu-FFT
su,0
su,Mu−1
su,Mu
su,2Mu−1
su,(N−1)Mu
su,NMu−1
UT u's Mu × N Doppler-delay domain
102 (120a)
111
GB: guard band

FIG. 3A

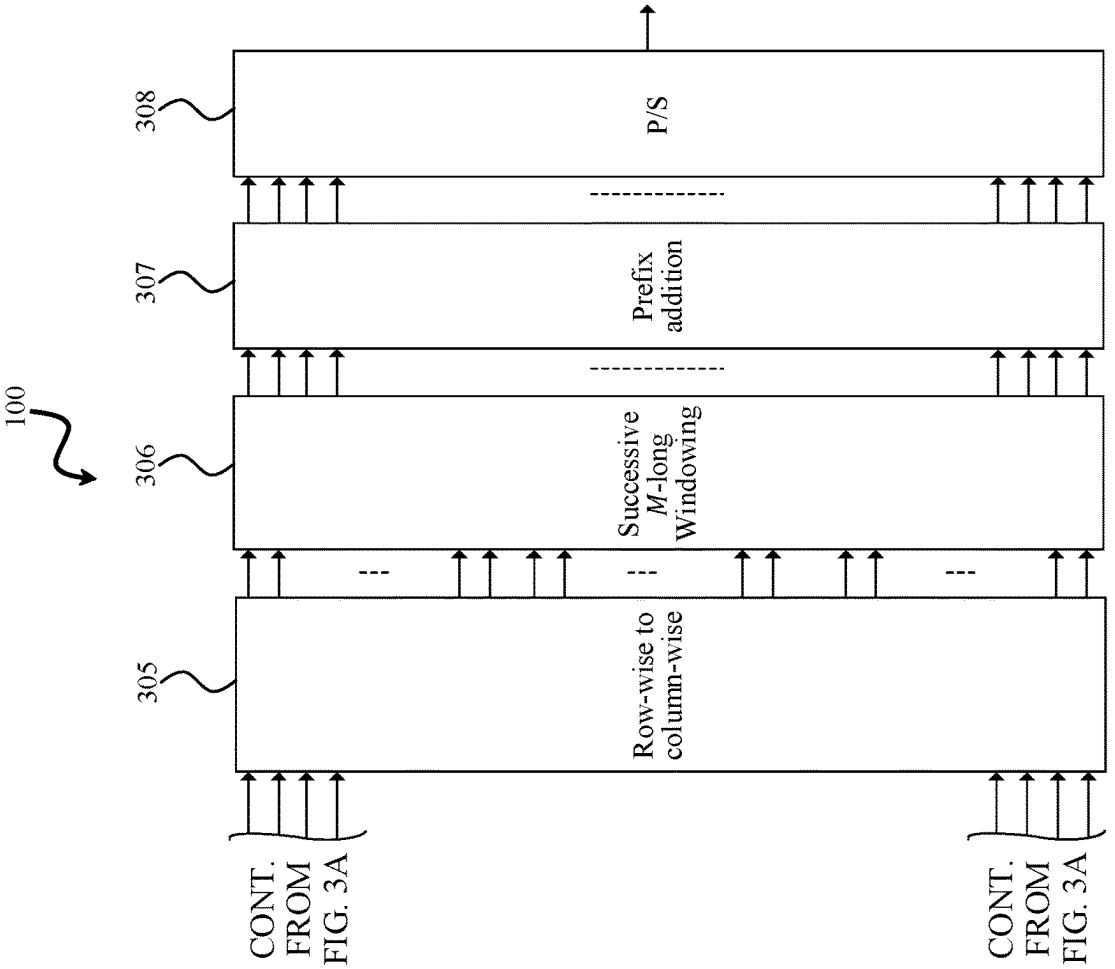
100
305
Row-wise to column-wise
306
Successive M-long Windowing
307
Prefix addition
308
P/S
CONT. FROM FIG. 3A
CONT. FROM FIG. 3A

FIG. 3B

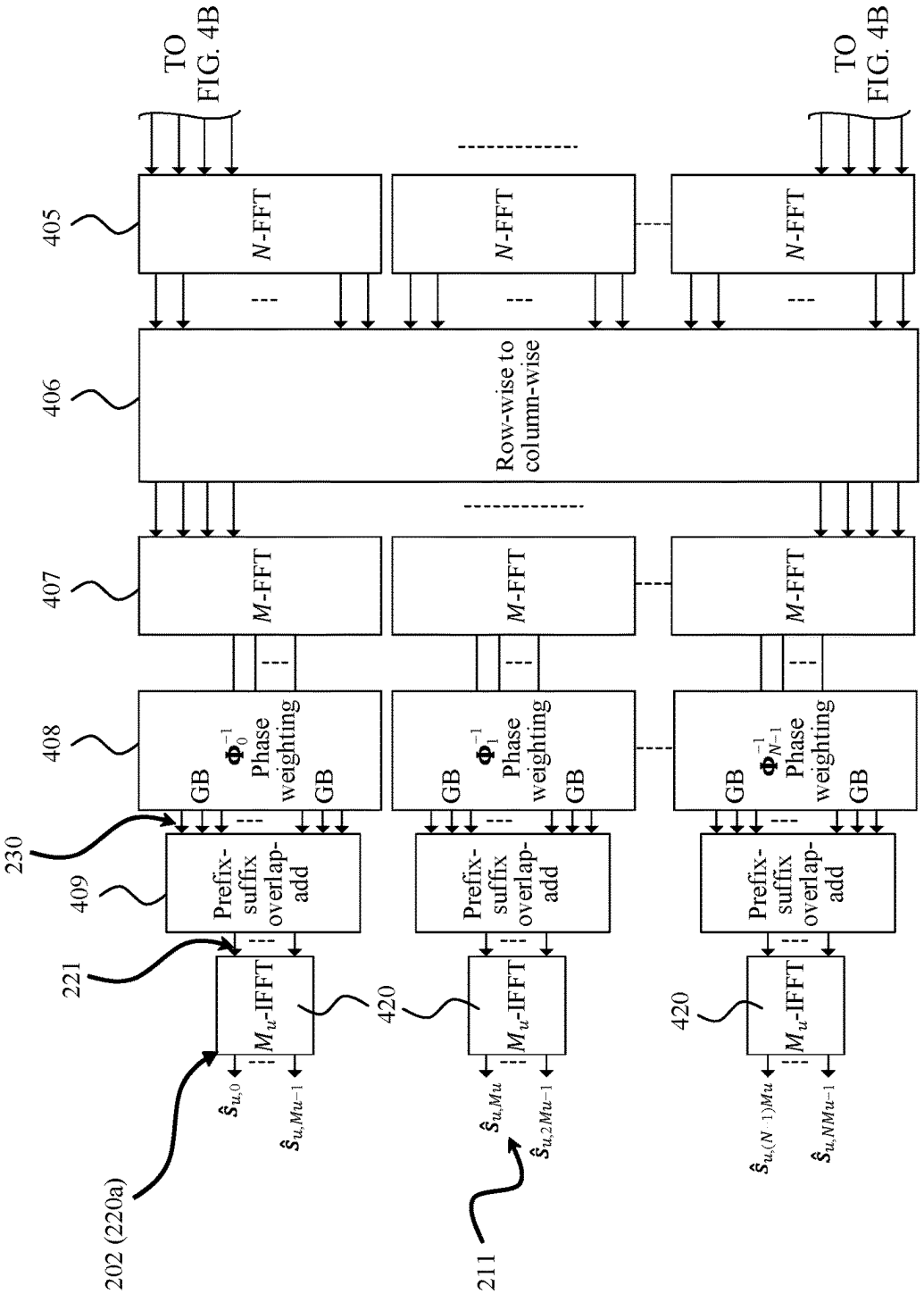
TO FIG. 4B
TO FIG. 4B
405
N-FFT
N-FFT
N-FFT
406
Row-wise to column-wise
407
M-FFT
M-FFT
M-FFT
408
GB
Φ_0^{-1} Phase weighting
GB
GB
Φ_1^{-1} Phase weighting
GB
GB
Φ_{N-1}^{-1} Phase weighting
GB
230
409
Prefix-suffix overlap-add
Prefix-suffix overlap-add
Prefix-suffix overlap-add
221
420
420
M_u-IFFT
M_u-IFFT
M_u-IFFT
$\hat{s}_{u,0}$
$\hat{s}_{u,Mu-1}$
$\hat{s}_{u,Mu}$
$\hat{s}_{u,2Mu-1}$
$\hat{s}_{u,(N-1)Mu}$
$\hat{s}_{u,NMu-1}$
202 (220a)
211
GB: guard band

FIG. 4A

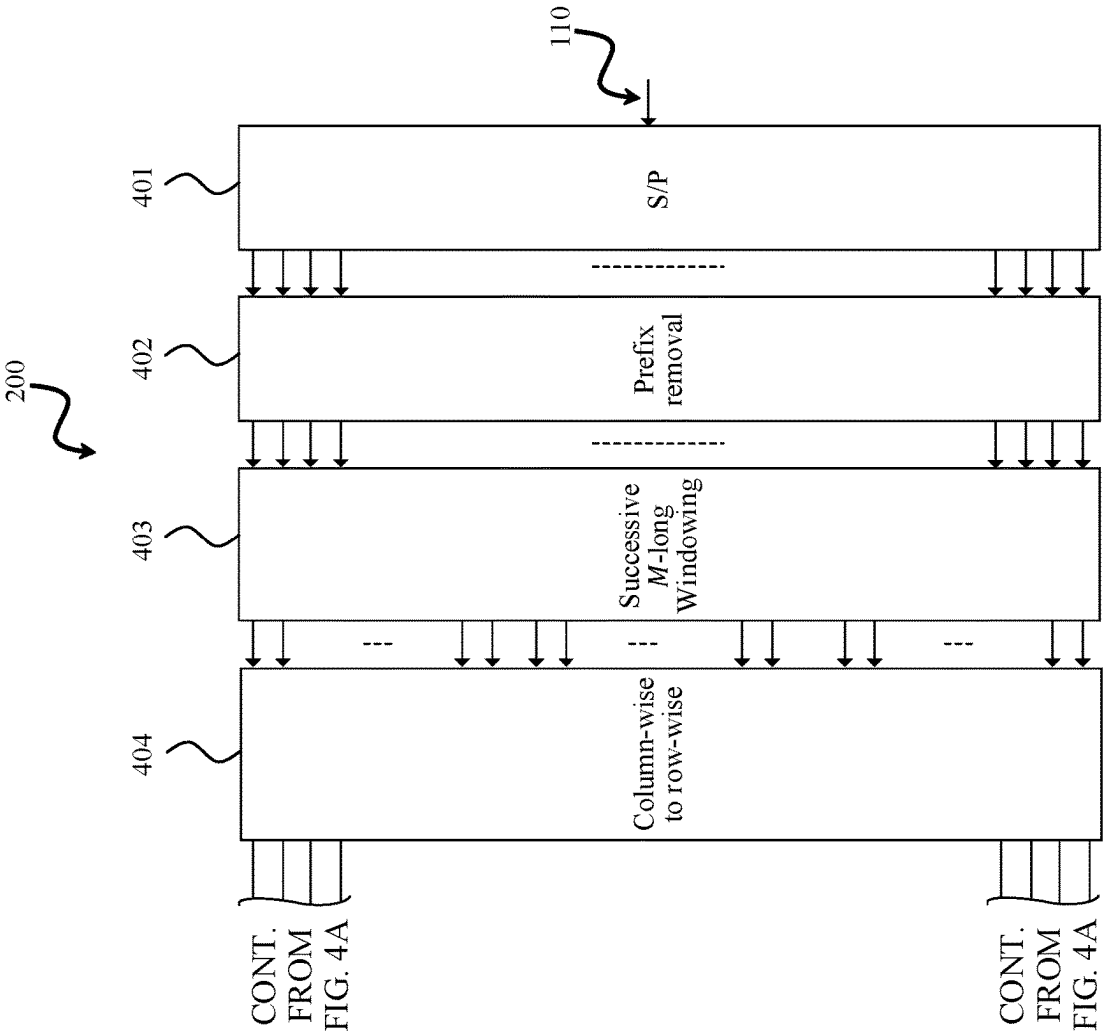
110
200
401
S/P
402
Prefix removal
403
Successive M-long Windowing
404
Column-wise to row-wise
CONT. FROM FIG. 4A
CONT. FROM FIG. 4A

FIG. 4B

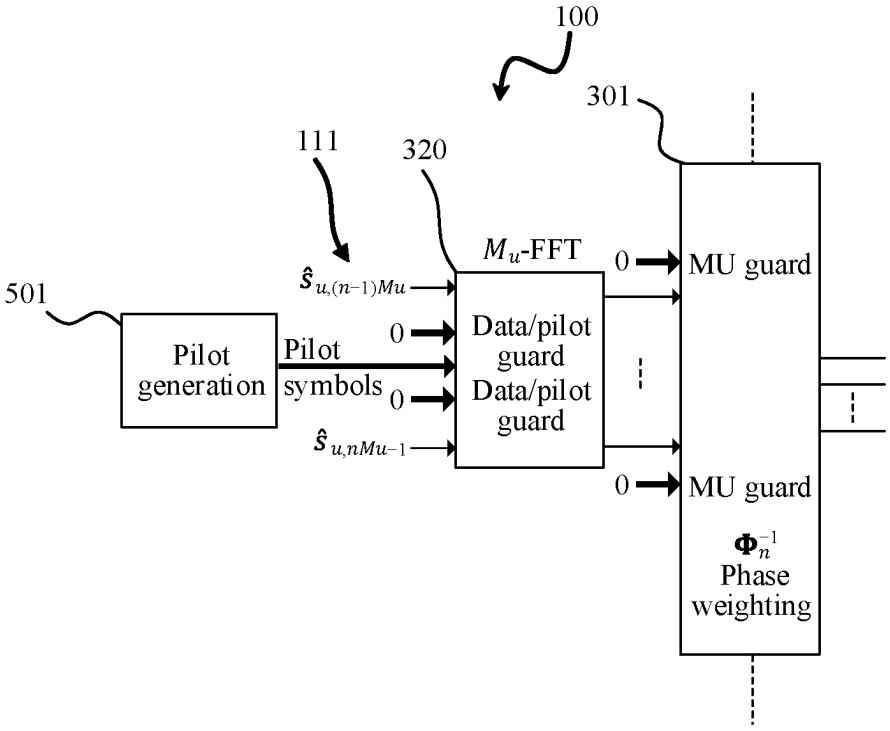
100
301
111
320
M_u-FFT
0
MU guard
501
$\hat{s}_{u,(n-1)Mu}$
0
Data/pilot guard
Pilot generation
Pilot symbols
0
Data/pilot guard
$\hat{s}_{u,nMu-1}$
0
MU guard
Φ_n^{-1}
Phase weighting

FIG. 5

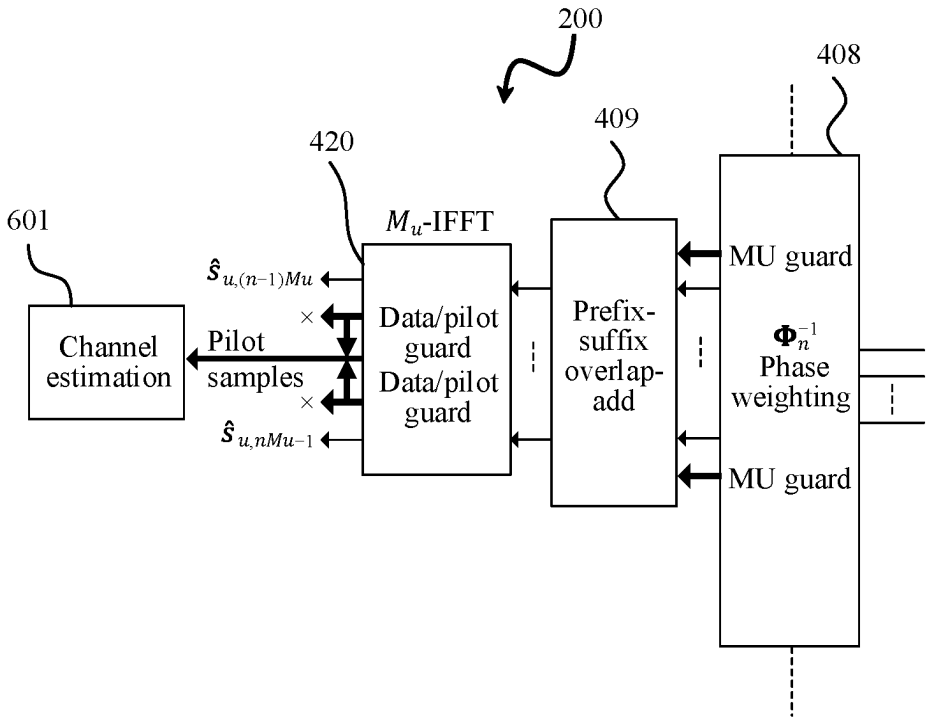
200
408
409
420
601
M_u-IFFT
$\hat{s}_{u,(n-1)Mu}$
Channel estimation
Pilot samples
Data/pilot guard
Data/pilot guard
$\hat{s}_{u,nMu-1}$
Prefix-suffix overlap-add
MU guard
Φ_n^{-1} Phase weighting
MU guard

FIG. 6

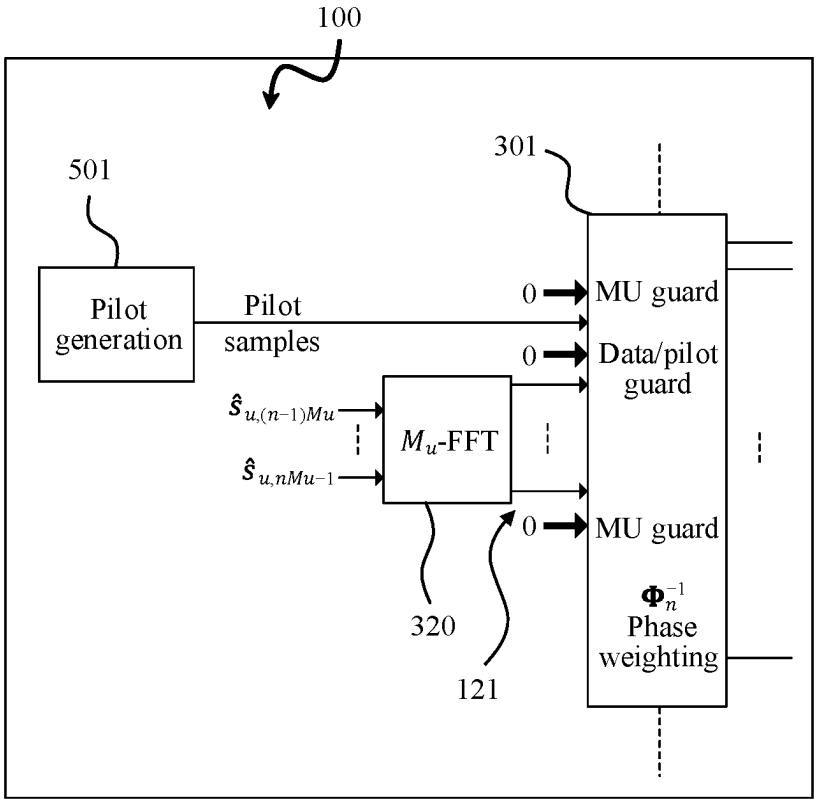
100
501
301
Pilot generation
Pilot samples
0
MU guard
0
Data/pilot guard
$\hat{s}_{u,(n-1)Mu}$
$\hat{s}_{u,nMu-1}$
M_u-FFT
0
MU guard
Φ_n^{-1} Phase weighting
320
121

FIG. 7A

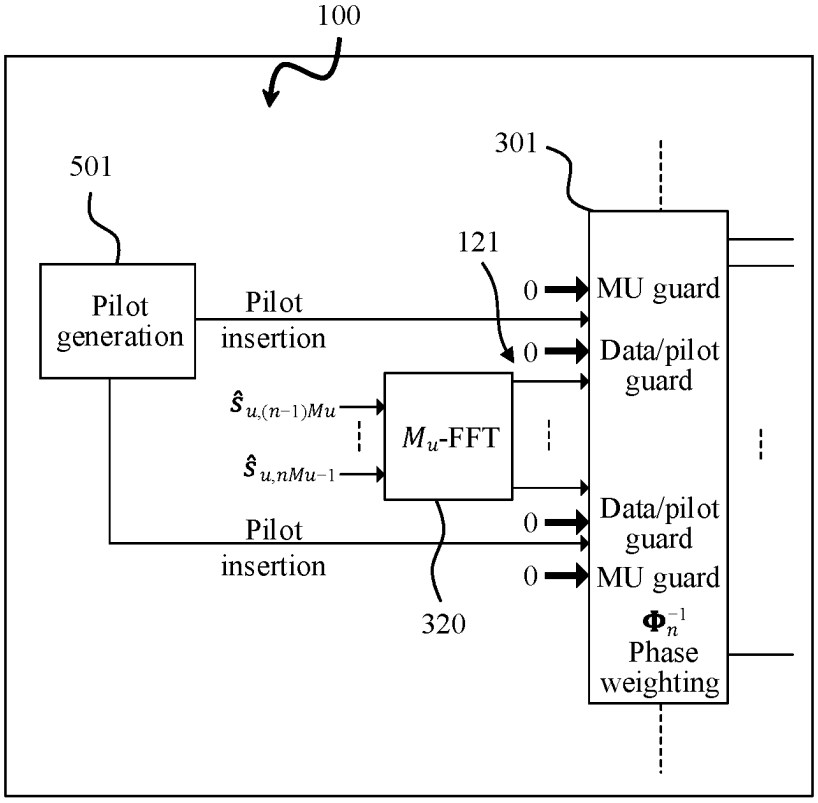
100
501
301
121
Pilot generation
Pilot insertion
0
MU guard
0
Data/pilot guard
$\hat{s}_{u,(n-1)Mu}$
$\hat{s}_{u,nMu-1}$
M_u-FFT
Data/pilot guard
Pilot insertion
0
0
MU guard
320
Φ_n^{-1}
Phase weighting

FIG. 7B

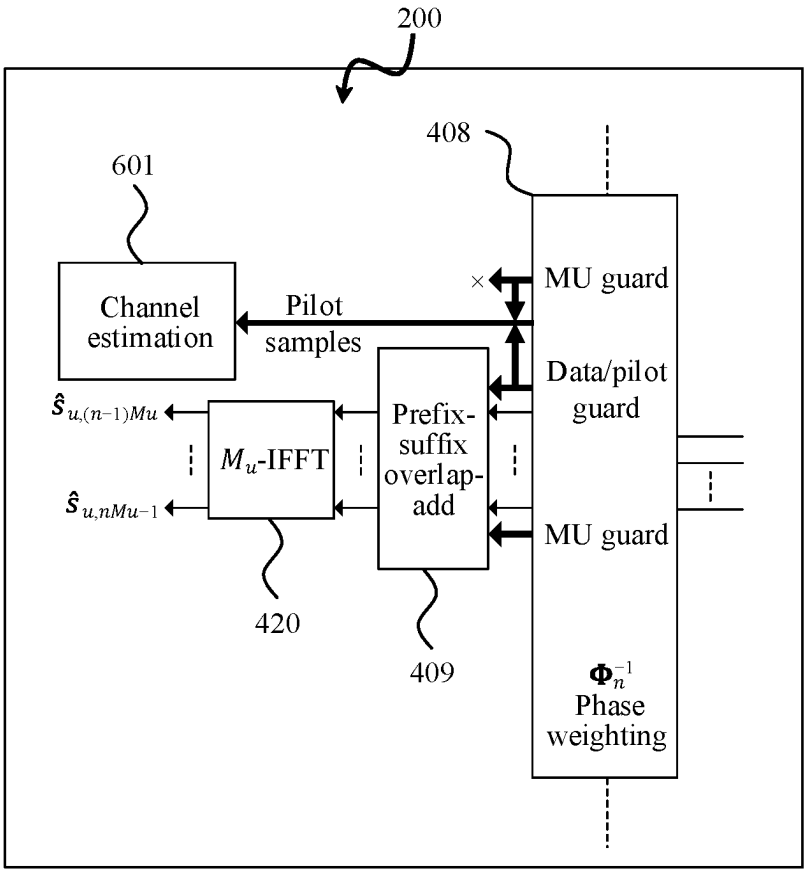
200
408
601
MU guard
Channel estimation
Pilot samples
Data/pilot guard
$\hat{s}_{u,(n-1)Mu}$
M_u-IFFT
Prefix-suffix overlap-add
$\hat{s}_{u,nMu-1}$
MU guard
420
409
Φ_n^{-1} Phase weighting

FIG. 8A

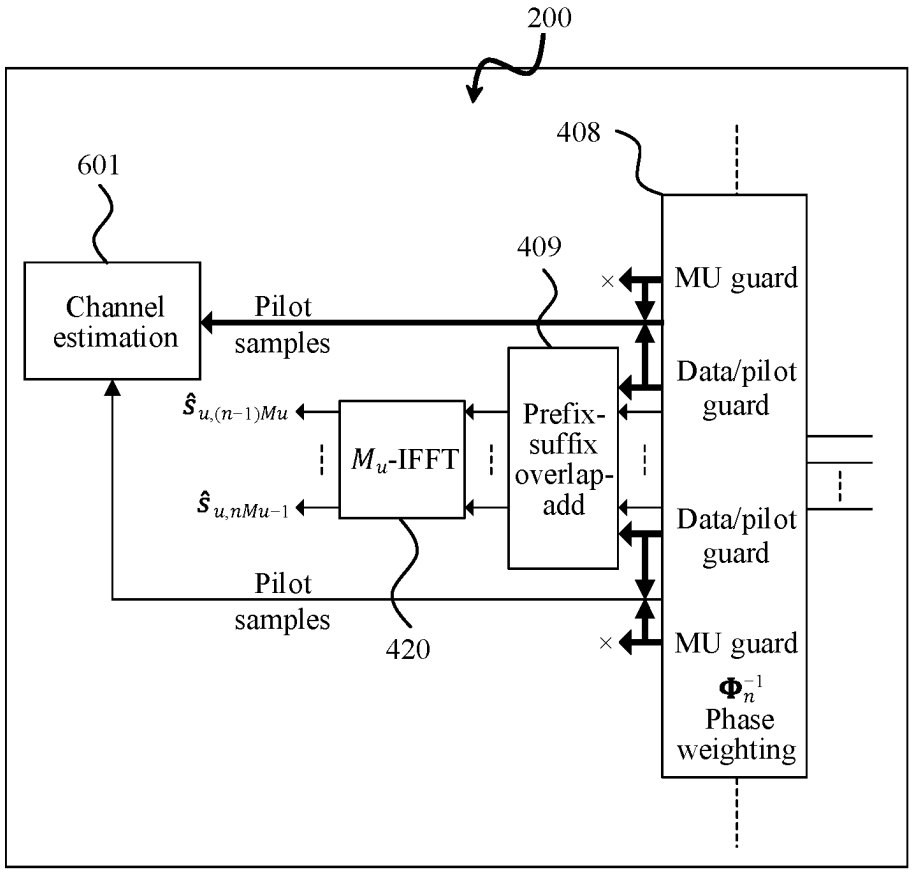
200
408
601
409
MU guard
Channel estimation
Pilot samples
Data/pilot guard
$\hat{s}_{u,(n-1)Mu}$
M_u-IFFT
Prefix-suffix overlap-add
$\hat{s}_{u,nMu-1}$
Data/pilot guard
Pilot samples
420
MU guard
Φ_n^{-1}
Phase weighting

FIG. 8B

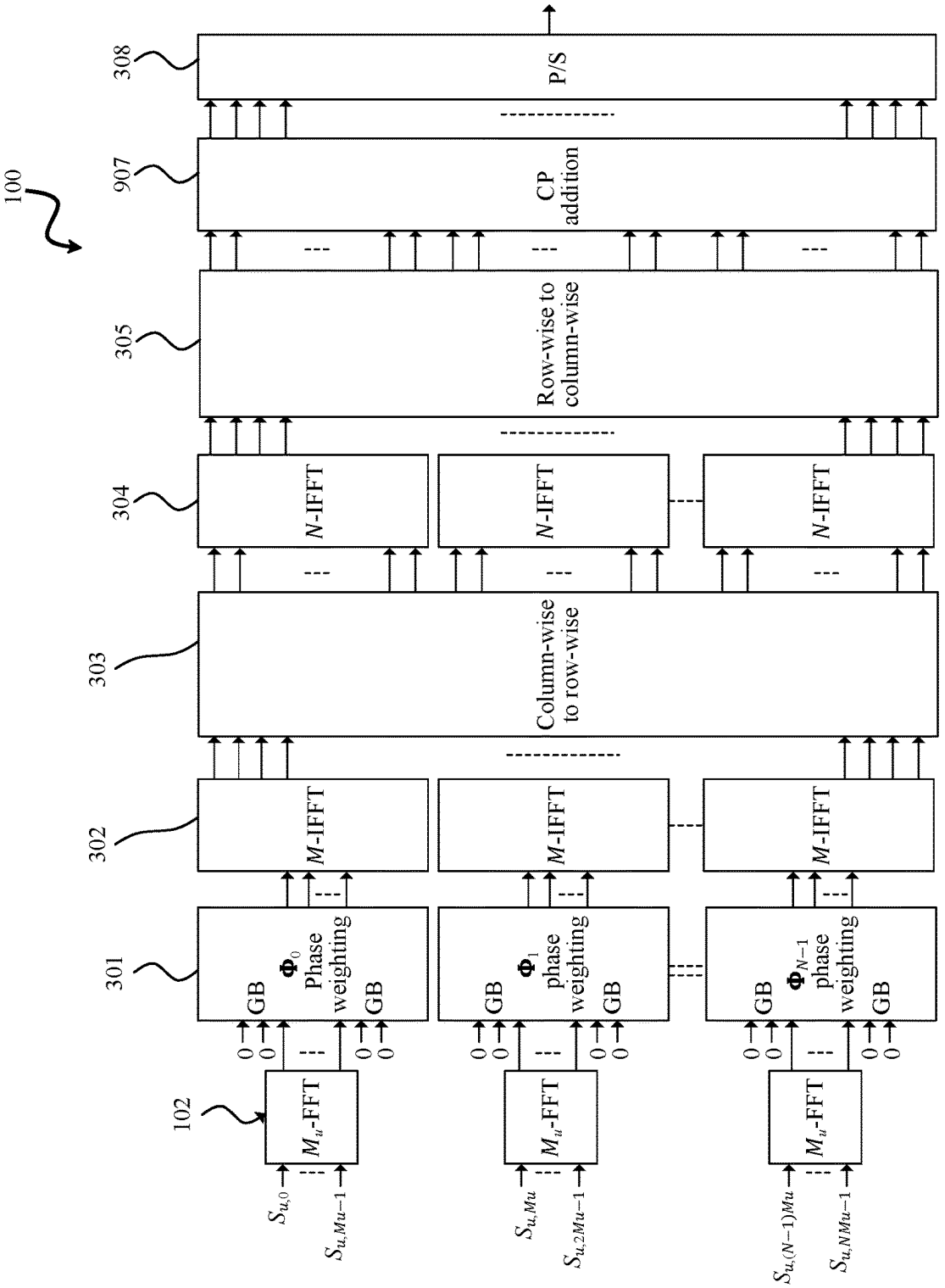
100
102
301
302
303
304
305
907
308
M_u-FFT
GB
Φ_0 Phase weighting
Φ_1 phase weighting
Φ_{N-1} phase weighting
M-IFFT
Column-wise to row-wise
N-IFFT
Row-wise to column-wise
CP addition
P/S
$S_{u,0}$
$S_{u,Mu-1}$
$S_{u,Mu}$
$S_{u,2Mu-1}$
$S_{u,(N-1)Mu}$
$S_{u,NMu-1}$

FIG. 9

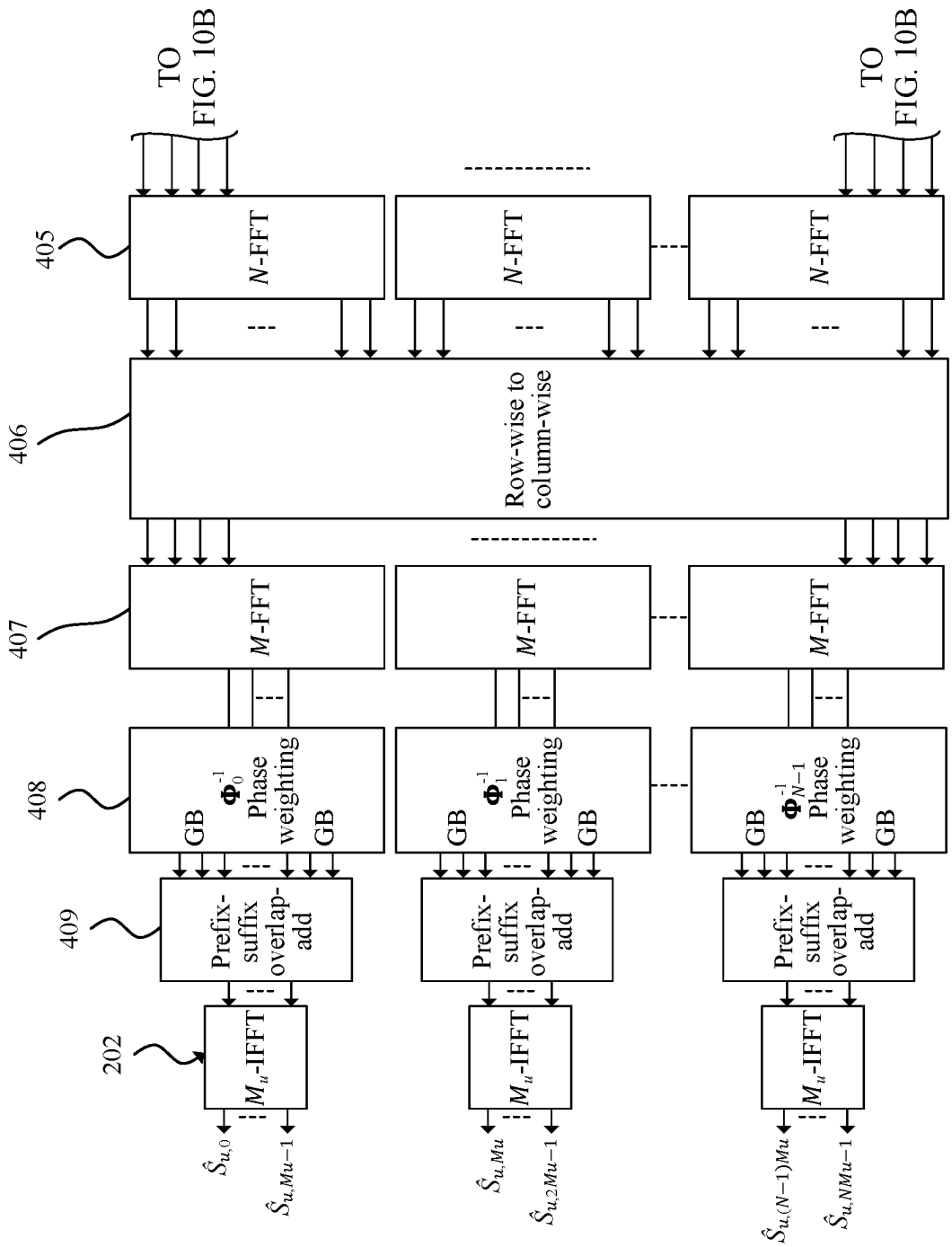
TO FIG. 10B
TO FIG. 10B
405
N-FFT
N-FFT
N-FFT
406
Row-wise to column-wise
407
M-FFT
M-FFT
M-FFT
408
GB
Φ_0^{-1} Phase weighting
GB
GB
Φ_1^{-1} Phase weighting
GB
GB
Φ_{N-1}^{-1} Phase weighting
GB
409
Prefix-suffix overlap-add
Prefix-suffix overlap-add
Prefix-suffix overlap-add
202
M_u-IFFT
M_u-IFFT
M_u-IFFT
$\hat{S}_{u,0}$
$\hat{S}_{u,Mu-1}$
$\hat{S}_{u,Mu}$
$\hat{S}_{u,2Mu-1}$
$\hat{S}_{u,(N-1)Mu}$
$\hat{S}_{u,NMu-1}$

FIG. 10A

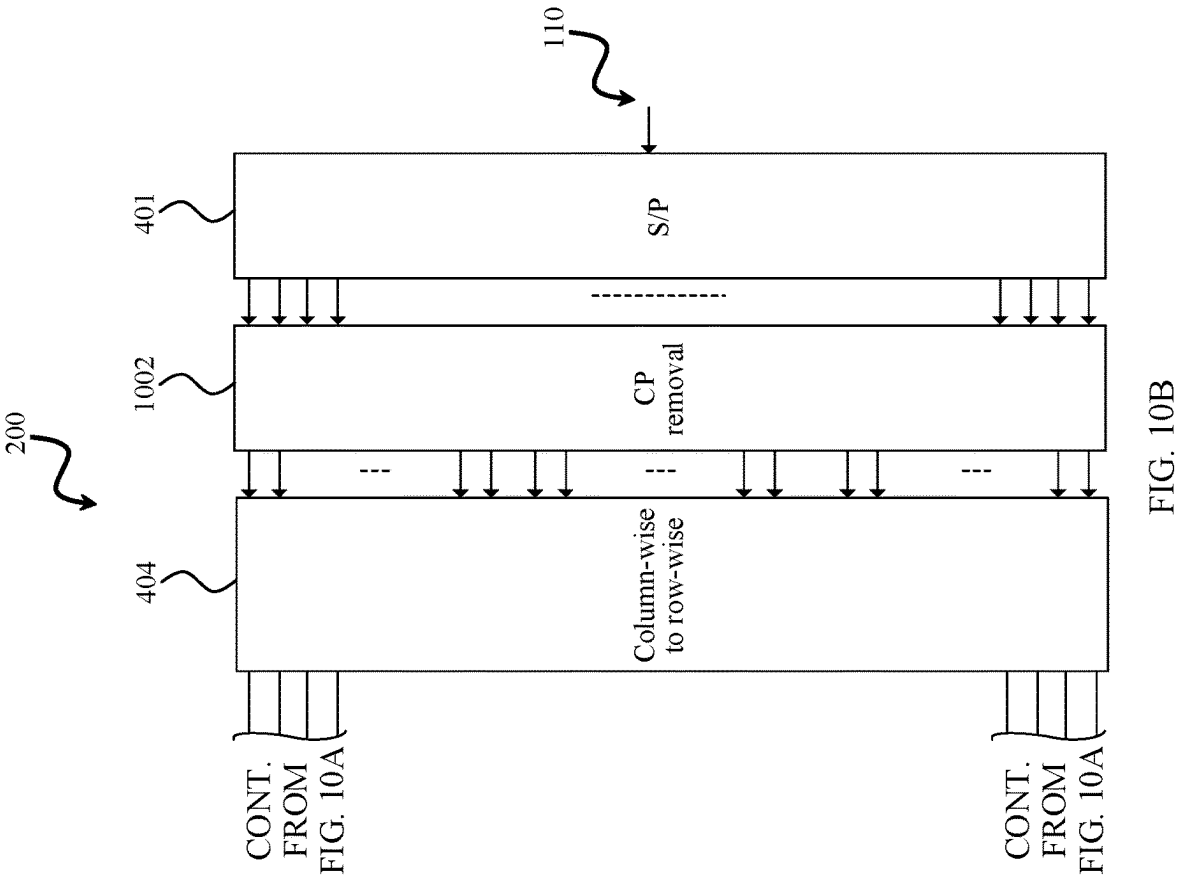
110
401
S/P
1002
CP removal
200
404
Column-wise to row-wise
CONT. FROM FIG. 10A
CONT. FROM FIG. 10A

FIG. 10B

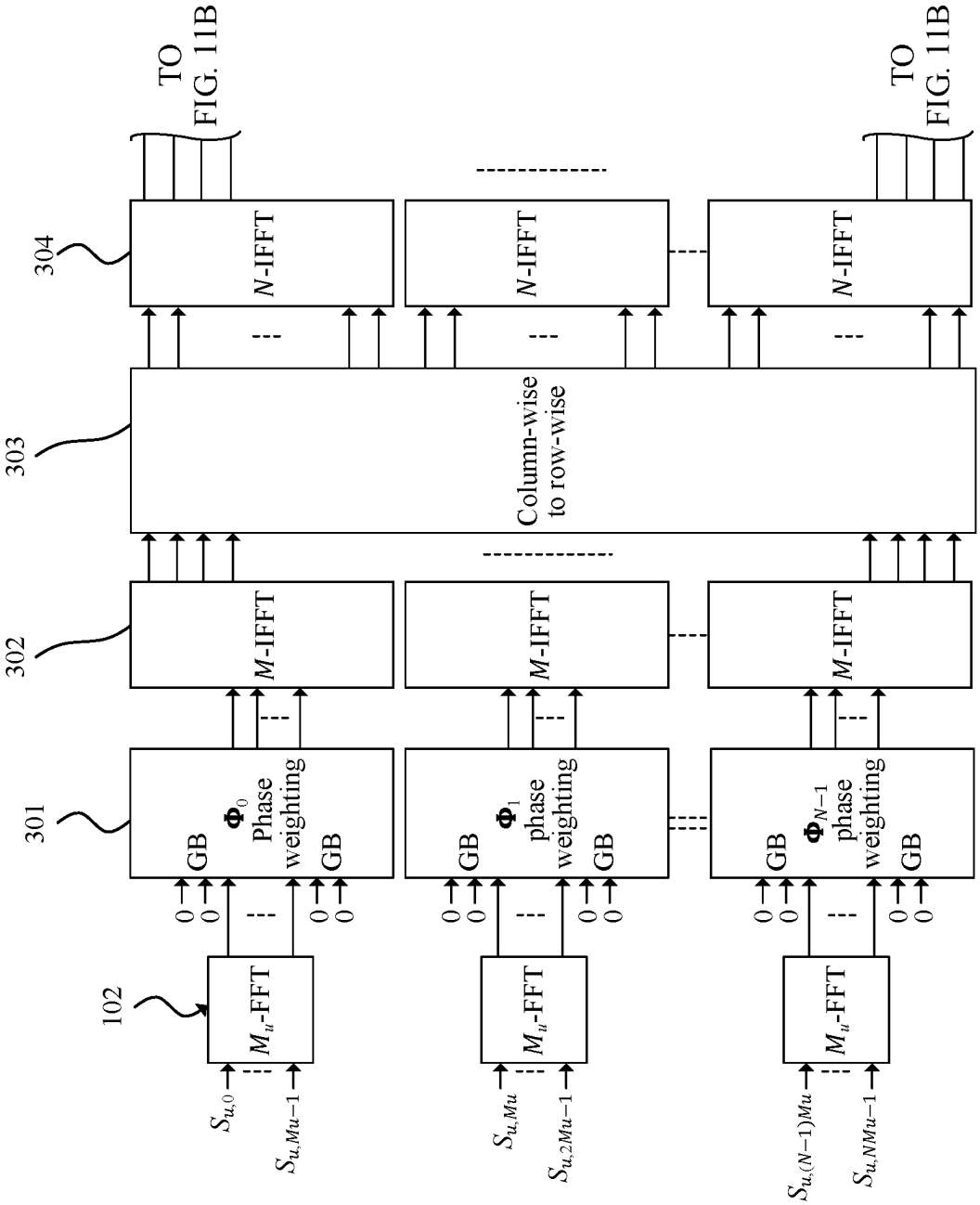
TO FIG. 11B
TO FIG. 11B
304
N-IFFT
N-IFFT
N-IFFT
303
Column-wise to row-wise
302
M-IFFT
M-IFFT
M-IFFT
301
GB
Φ0 Phase weighting
GB
GB
Φ1 phase weighting
GB
GB
ΦN−1 phase weighting
GB
102
Mu-FFT
Mu-FFT
Mu-FFT
Su,0
Su,Mu−1
Su,Mu
Su,2Mu−1
Su,(N−1)Mu
Su,NMu−1

FIG. 11A

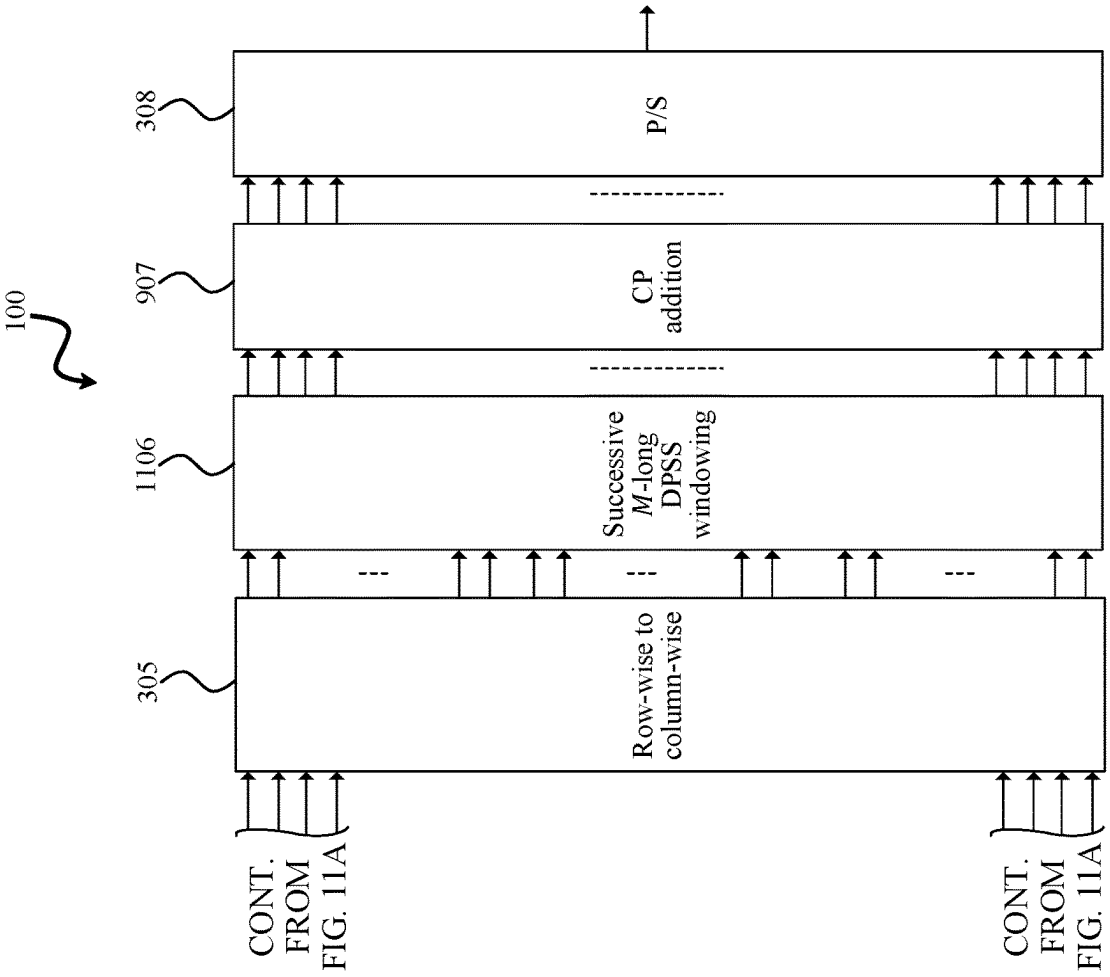
100
305
Row-wise to column-wise
1106
Successive M-long DPSS windowing
907
CP addition
308
P/S
CONT. FROM FIG. 11A
CONT. FROM FIG. 11A

FIG. 11B

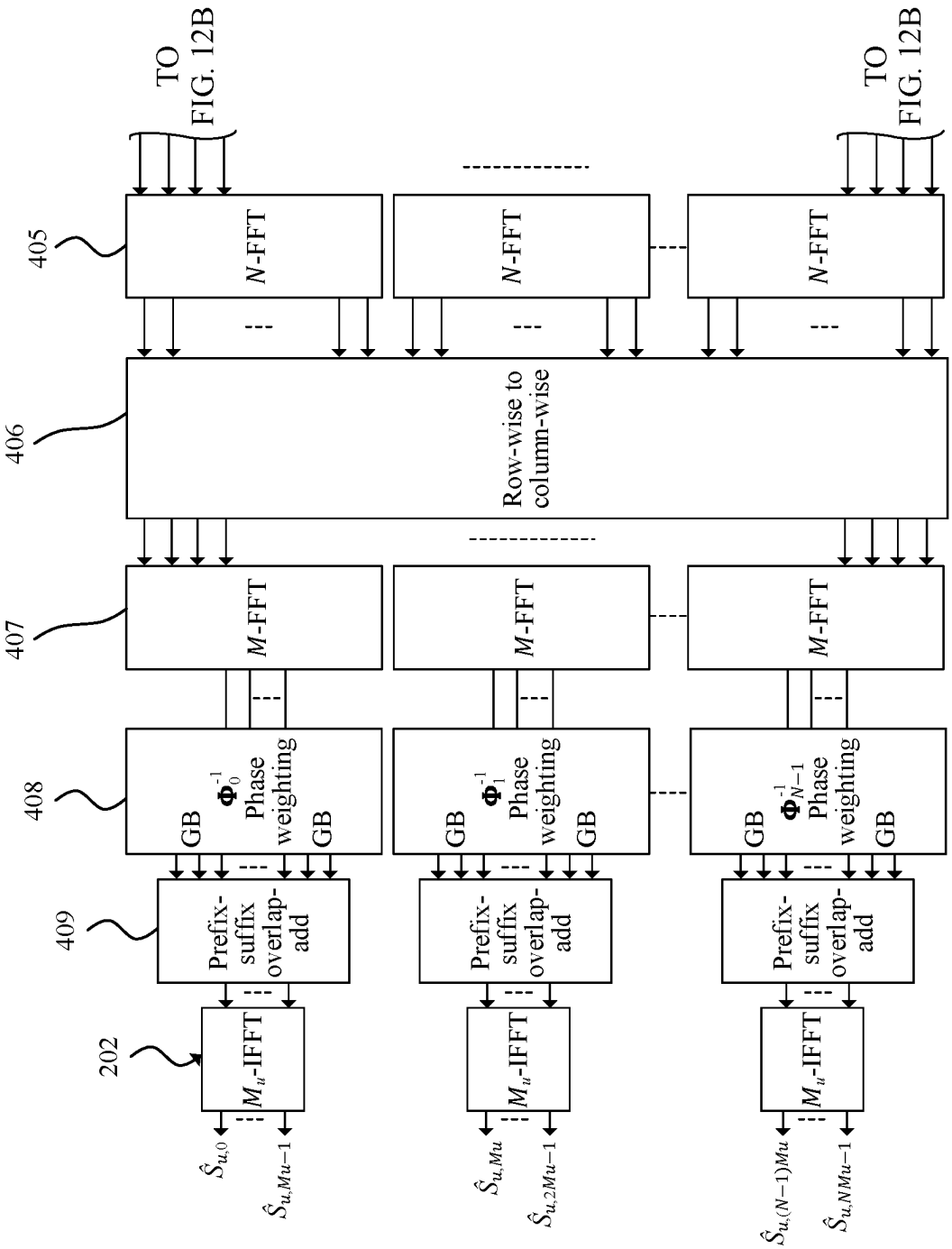
TO FIG. 12B
TO FIG. 12B
405
N-FFT
N-FFT
N-FFT
406
Row-wise to column-wise
407
M-FFT
M-FFT
M-FFT
408
GB
Φ_0^{-1} Phase weighting
GB
GB
Φ_1^{-1} Phase weighting
GB
GB
Φ_{N-1}^{-1} Phase weighting
GB
409
Prefix-suffix overlap-add
Prefix-suffix overlap-add
Prefix-suffix overlap-add
202
M_u-IFFT
M_u-IFFT
M_u-IFFT
$\hat{S}_{u,0}$
$\hat{S}_{u,Mu-1}$
$\hat{S}_{u,Mu}$
$\hat{S}_{u,2Mu-1}$
$\hat{S}_{u,(N-1)Mu}$
$\hat{S}_{u,NMu-1}$

FIG. 12A

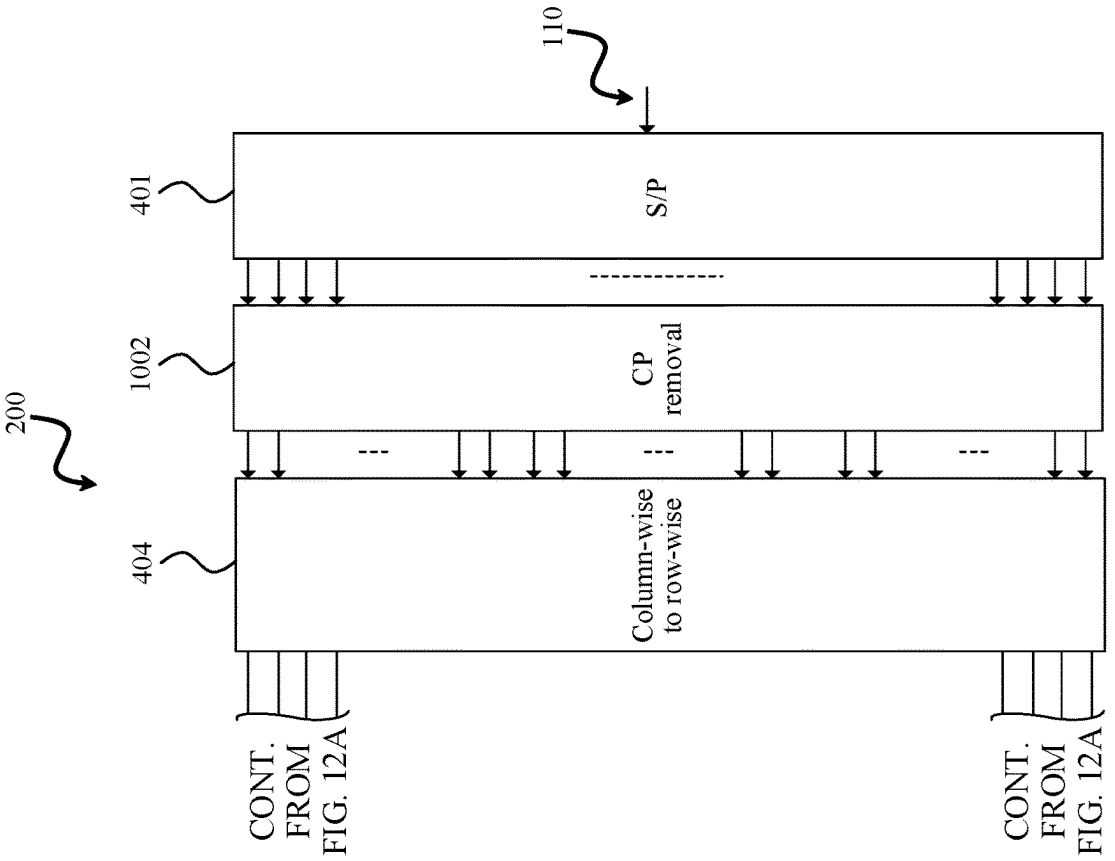
110
401
S/P
1002
CP removal
200
404
Column-wise to row-wise
CONT. FROM FIG. 12A
CONT. FROM FIG. 12A

FIG. 12B

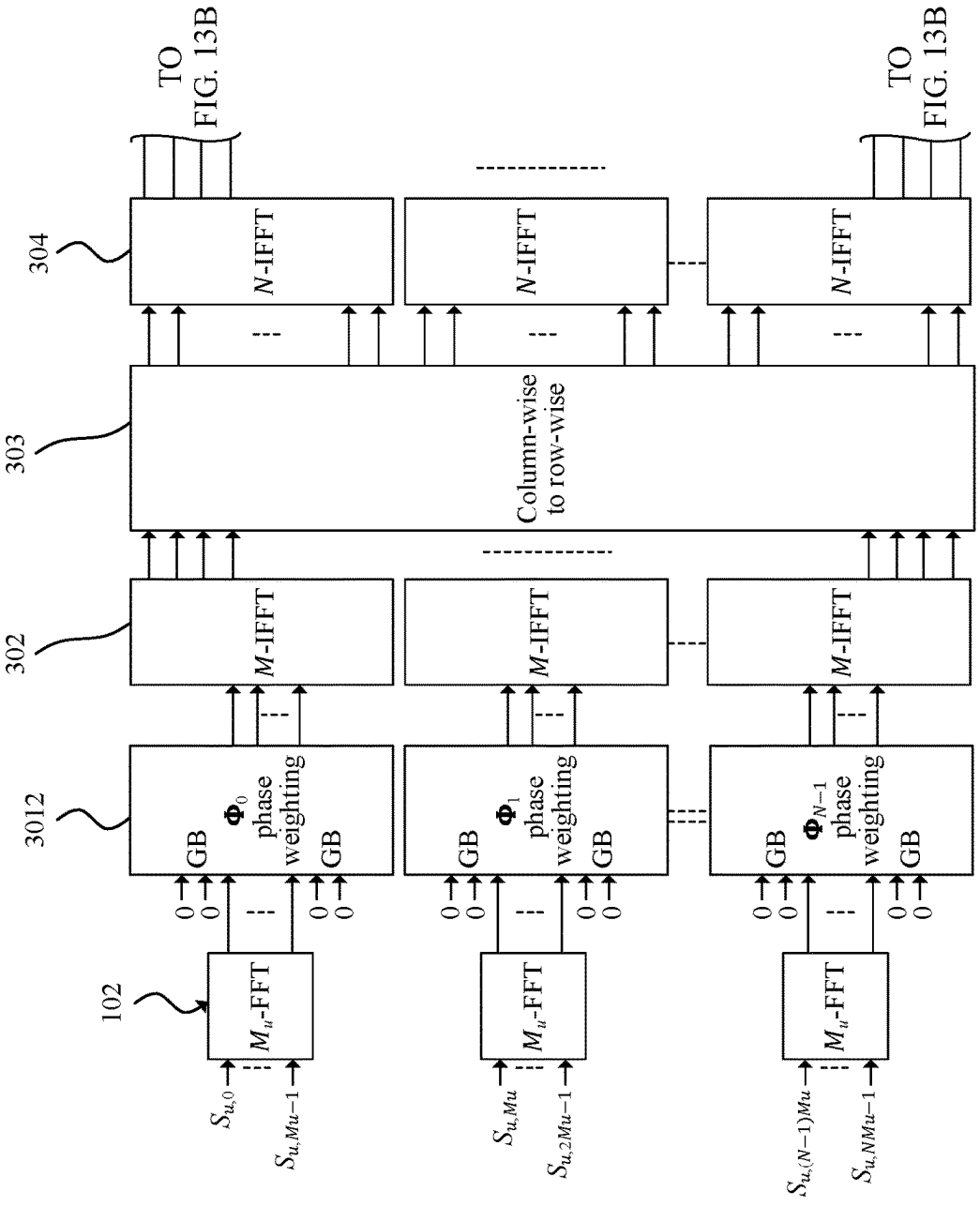
TO FIG. 13B
TO FIG. 13B
304
N-IFFT
303
Column-wise to row-wise
302
M-IFFT
3012
GB
Φ_0 phase weighting
Φ_1 phase weighting
Φ_{N-1} phase weighting
102
M_u-FFT
$S_{u,0}$
$S_{u,Mu-1}$
$S_{u,Mu}$
$S_{u,2Mu-1}$
$S_{u,(N-1)Mu}$
$S_{u,NMu-1}$
GB: multi-user guard band

FIG. 13A

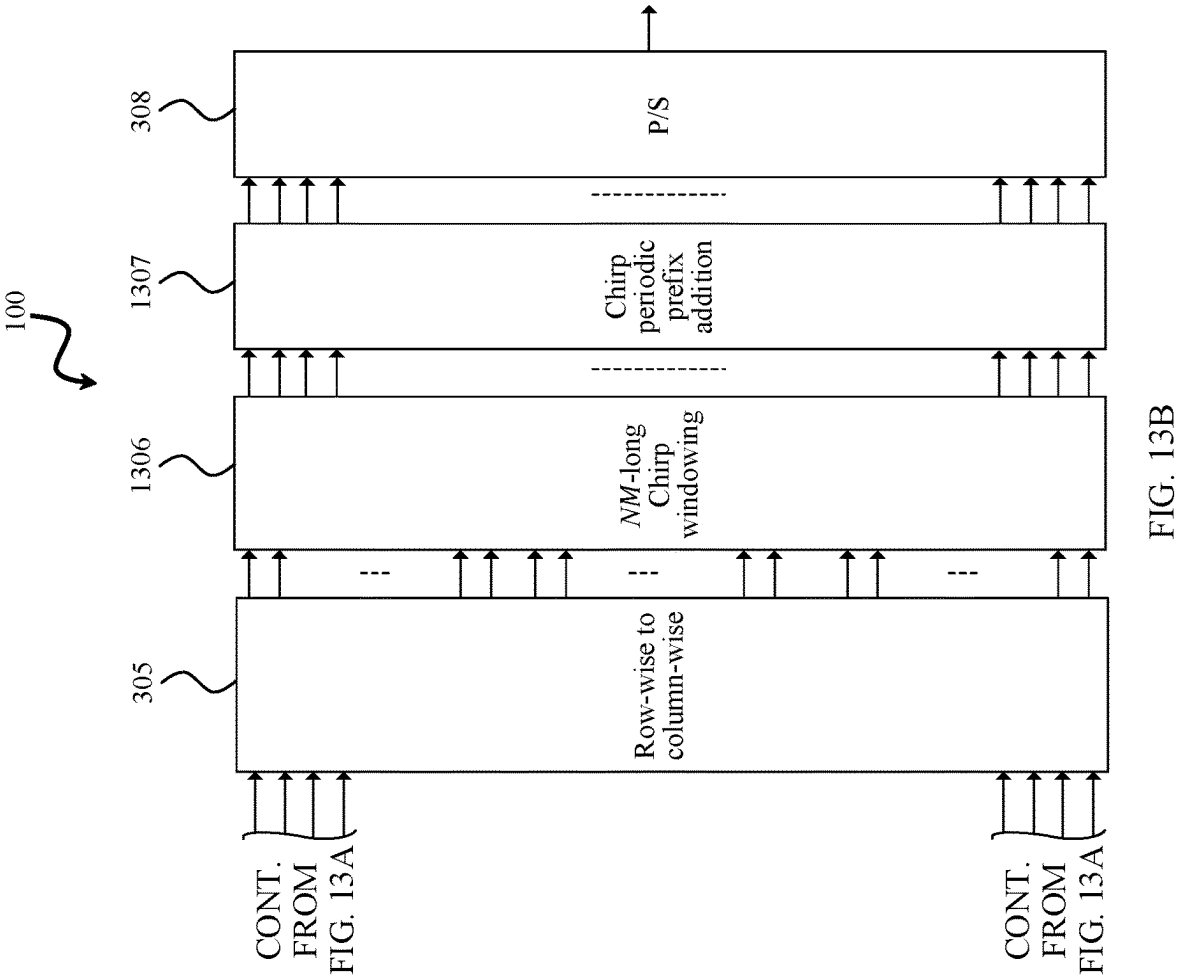
100
308
P/S
1307
Chirp periodic prefix addition
1306
NM-long Chirp windowing
305
Row-wise to column-wise
CONT. FROM FIG. 13A
CONT. FROM FIG. 13A

FIG. 13B

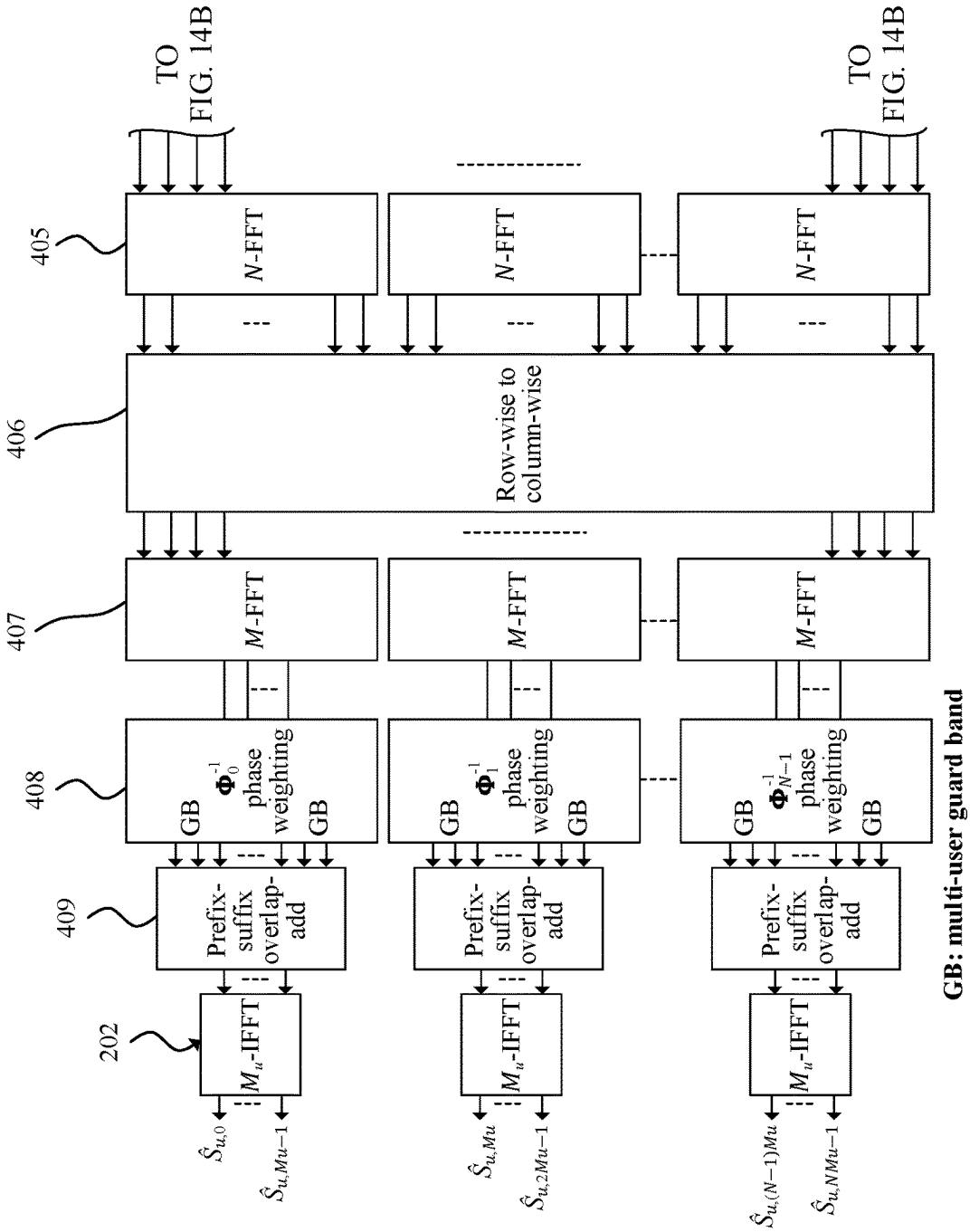
TO FIG. 14B
TO FIG. 14B
405
406
407
408
409
202
N-FFT
N-FFT
N-FFT
Row-wise to column-wise
M-FFT
M-FFT
M-FFT
GB
Φ_0^{-1} phase weighting
GB
GB
Φ_1^{-1} phase weighting
GB
GB
Φ_{N-1}^{-1} phase weighting
GB
Prefix-suffix overlap-add
Prefix-suffix overlap-add
Prefix-suffix overlap-add
M_u-IFFT
M_u-IFFT
M_u-IFFT
$\hat{S}_{u,0}$
$\hat{S}_{u,Mu-1}$
$\hat{S}_{u,Mu}$
$\hat{S}_{u,2Mu-1}$
$\hat{S}_{u,(N-1)Mu}$
$\hat{S}_{u,NMu-1}$
GB: multi-user guard band

FIG. 14A

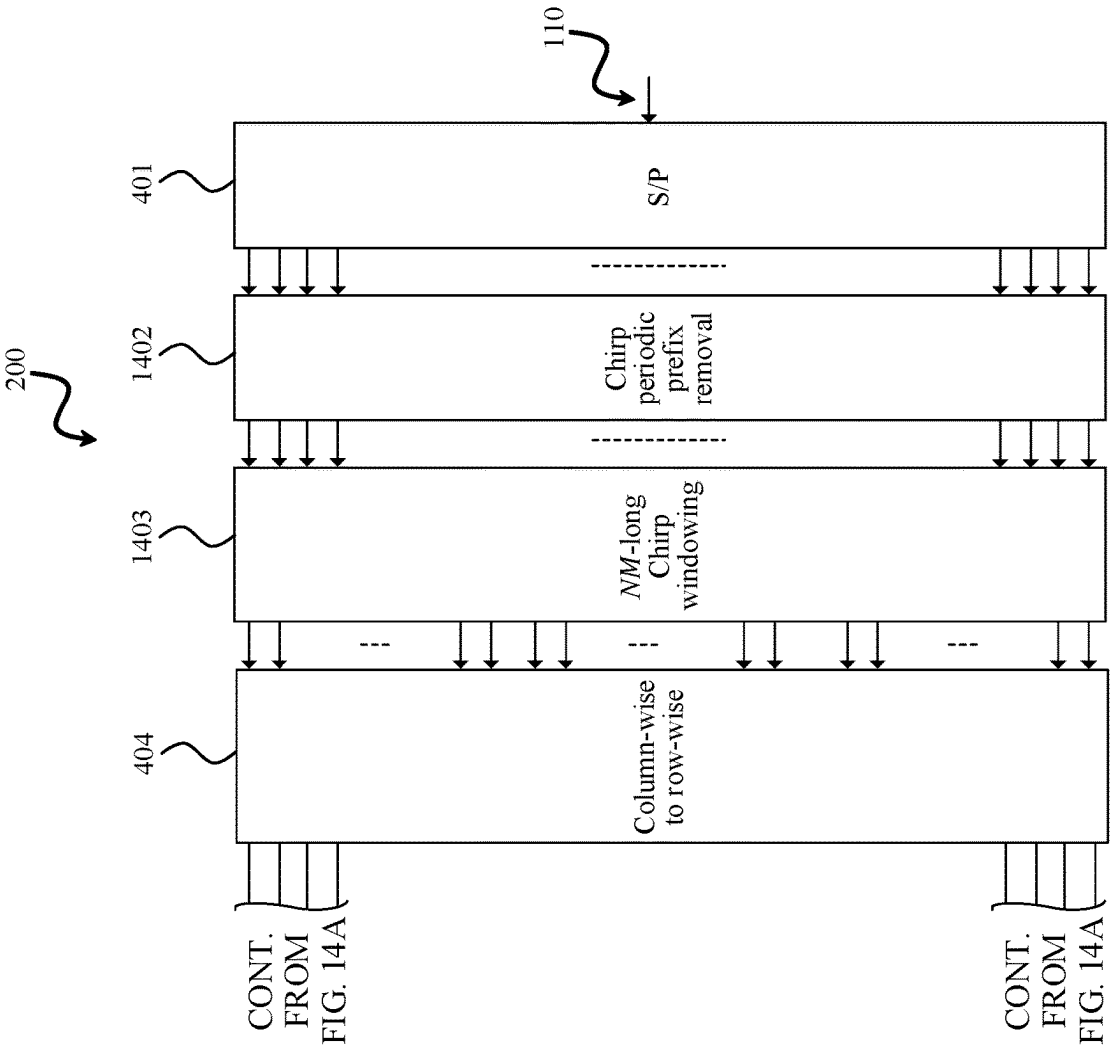
110
401
S/P
1402
Chirp periodic prefix removal
200
1403
NM-long Chirp windowing
404
Column-wise to row-wise
CONT. FROM FIG. 14A
CONT. FROM FIG. 14A

FIG. 14B

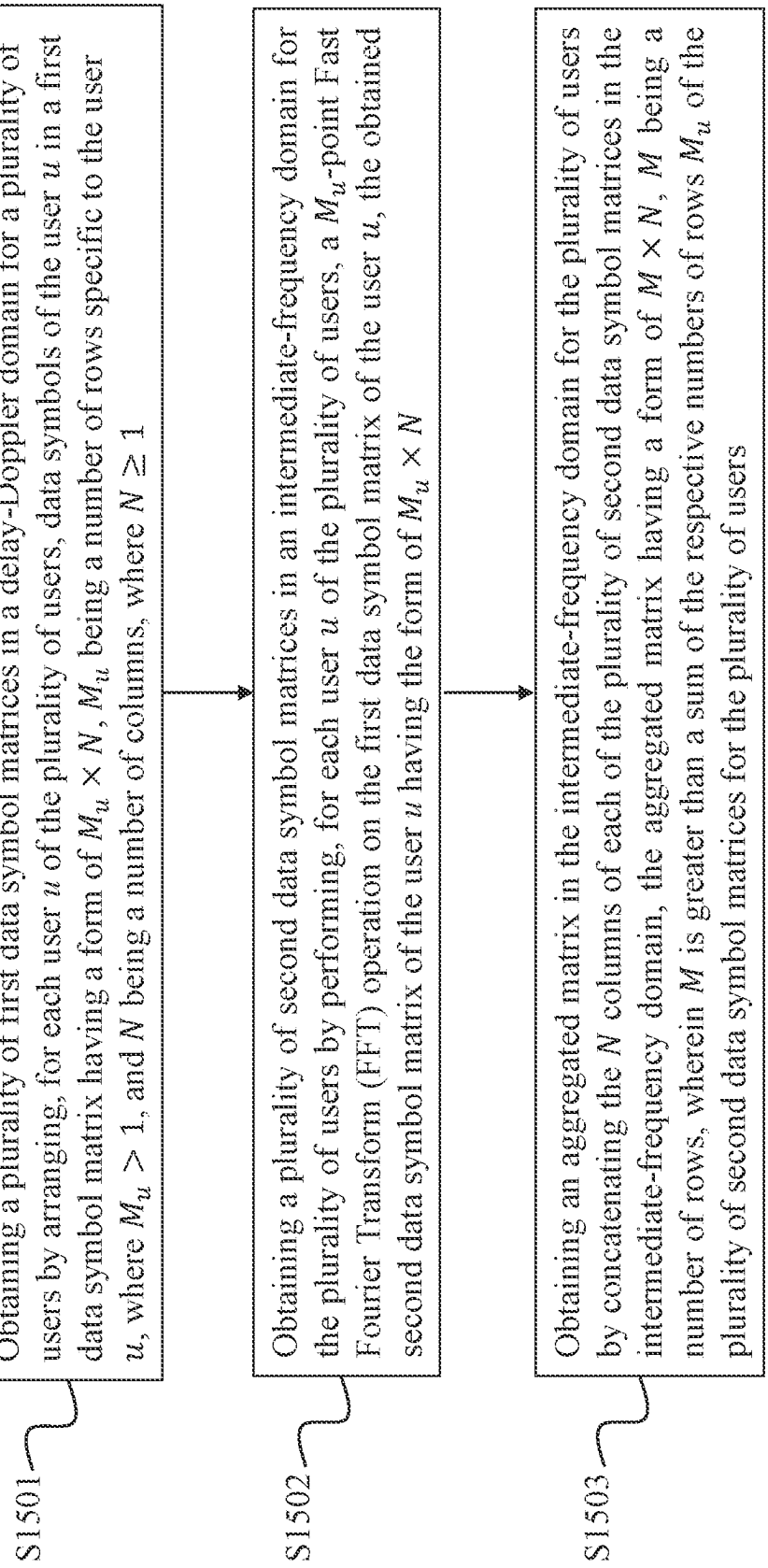
1500
S1501
Obtaining a plurality of first data symbol matrices in a delay-Doppler domain for a plurality of users by arranging, for each user u of the plurality of users, data symbols of the user u in a first data symbol matrix having a form of $M_u \times N$, M_u being a number of rows specific to the user u, where $M_u > 1$, and N being a number of columns, where $N \geq 1$
S1502
Obtaining a plurality of second data symbol matrices in an intermediate-frequency domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point Fast Fourier Transform (FFT) operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of $M_u \times N$
S1503
Obtaining an aggregated matrix in the intermediate-frequency domain for the plurality of users by concatenating the N columns of each of the plurality of second data symbol matrices in the intermediate-frequency domain, the aggregated matrix having a form of $M \times N$, M being a number of rows, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of second data symbol matrices for the plurality of users

FIG. 15

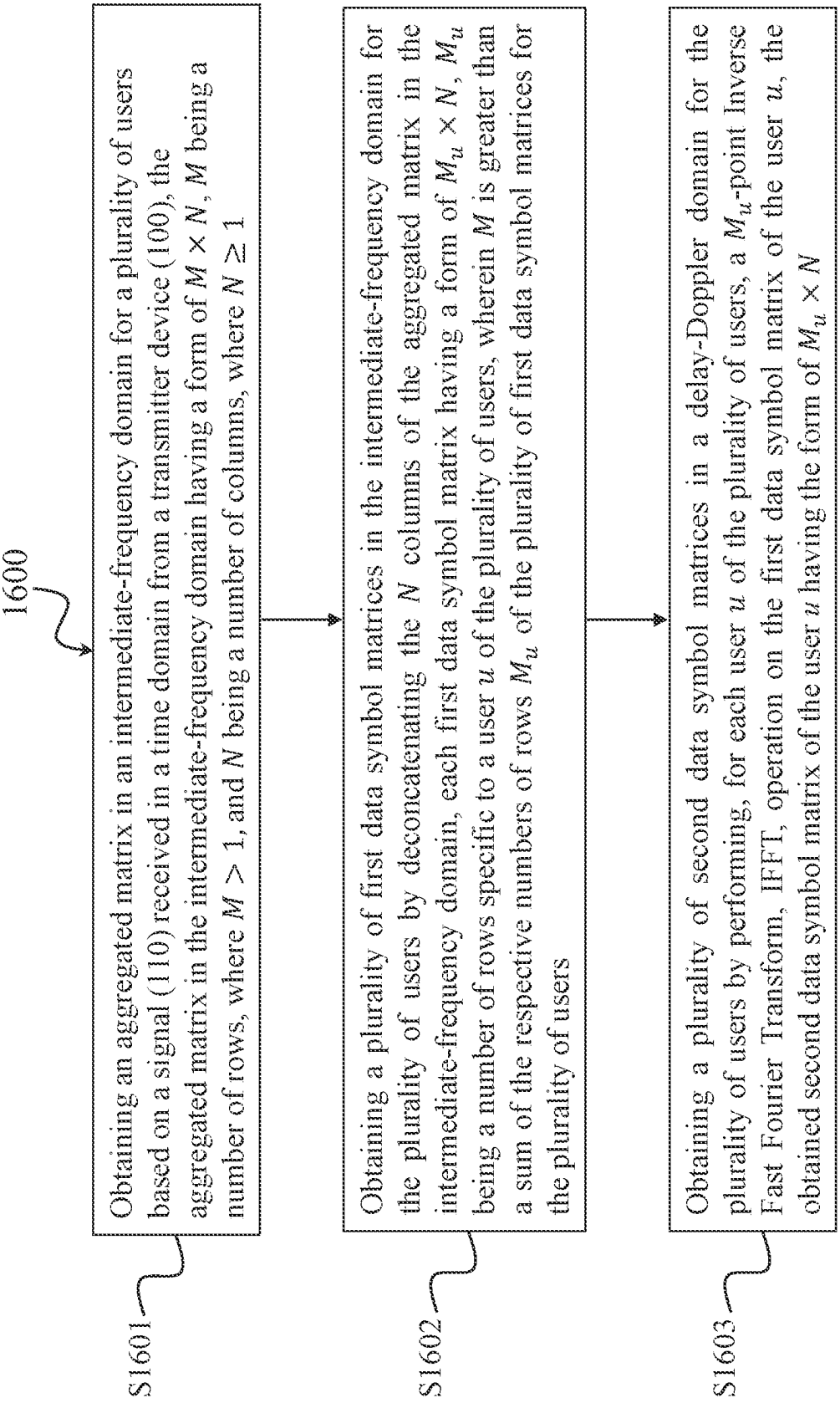
1600
S1601
Obtaining an aggregated matrix in an intermediate-frequency domain for a plurality of users based on a signal (110) received in a time domain from a transmitter device (100), the aggregated matrix in the intermediate-frequency domain having a form of $M \times N$, M being a number of rows, where $M > 1$, and N being a number of columns, where $N \geq 1$
S1602
Obtaining a plurality of first data symbol matrices in the intermediate-frequency domain for the plurality of users by deconcatenating the N columns of the aggregated matrix in the intermediate-frequency domain, each first data symbol matrix having a form of $M_u \times N$, M_u being a number of rows specific to a user u of the plurality of users, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of first data symbol matrices for the plurality of users
S1603
Obtaining a plurality of second data symbol matrices in a delay-Doppler domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point Inverse Fast Fourier Transform, IFFT, operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of $M_u \times N$

FIG. 16

TRANSMITTER DEVICE AND RECEIVER DEVICE FOR A WIRELESS COMMUNICATION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of International Application No. PCT/EP2021/054786, filed on Feb. 26, 2021, the disclosure of which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

The present disclosure relates generally to the field of wireless communication, and particularly to a transmitter device and a receiver device for a wireless communication system. A transmitter device, a receiver device, and corresponding methods for a wireless communication system are disclosed. The disclosed transmitter device, receiver device, and methods may support low-overhead multiple access for a layered Fast Fourier Transform (FFT)-based wireless communication.

BACKGROUND

Generally, in wireless communication systems, special signals known by receiver devices, e.g., channel state information reference signals (CSI-RS) and demodulation reference signal (DMRS) pilots in long-term evolution (LTE) and new radio (NR) systems, are normally emitted by transmitter devices. The receiver devices can generate channel state information (CSI) estimates about their wireless links to the transmitter device. These special signals (i.e., the CSI-RS, DMRS, etc.) do not carry data, and may thus cause an overhead that should be kept as low as possible in wireless communication systems.

Furthermore, another overhead in wireless communication systems may come from null or guard symbols that are used to separate pilot symbols from data symbols. For example, the null or guard symbols may be used to prevent, or at least reduce, interference from data during channel estimation or pilots during data detection.

Moreover, another source of overhead in wireless communication systems may come from null or guard symbols that are used to separate data and pilot symbols originating from, or destined to, different wireless terminals for the sake of preventing, or at least reducing, multi-user interference.

The overhead levels, which are related to both pilot symbols and guard symbols and are needed for operating wireless communication systems, tend to increase in high-mobility scenarios (i.e., in cases where the transmitter device and the receiver device are moving rapidly relative to each other). In high-mobility scenarios, transmitted signals may be received (i.e., by the receiver device) with larger values of the so-called Doppler frequency shift. Further, different contributions, i.e., components, in the received signal originating from different reflection and scattering off objects in the environment are typically received with different values of the Doppler frequency shift. The difference between the smallest and the largest Doppler shift in the received signal is called the Doppler frequency spread. In existing wireless communication systems, the larger the Doppler spread is, the higher a challenge it poses to data detection at the receiving terminals.

Conventional waveforms for wireless communication systems (for example, waveforms of current wireless standards, up to and including the fifth Generation (5G)), are not designed for mobility. However, they may be tuned to compensate for that lack of design, e.g., by making the symbols shorter in Orthogonal Frequency-Division Multiplexing (OFDM).

However, an issue of such compensations is that they may cause losses in spectral efficiency (as in the OFDM case), or other performance metrics.

Some conventional devices and methods are based on asymmetric OFDM (A-OFDM). A-OFDM was originally proposed as an alternative to OFDM, with a lower peak-to-average power ratio (PAPR). It is based on using a layered-IFFT transformation to generate the signal to be transmitted. Further, it was suggested that A-OFDM is more robust than OFDM against the Doppler frequency spread, i.e., in mobility scenarios.

However, an issue of A-OFDM is that the receiver does not employ a layered-FFT transformation and thus that the data symbols may not be detected at the receiver side in the delay-Doppler domain. The full diversity of the high-mobility channel is thus not guaranteed by the use of the A-OFDM transceiver. The delay-Doppler domain is the domain defined by a specific layered-FFT mathematical transformation called the Zak transformation. Detecting the data symbols in the delay-Doppler domain may be based on applying the appropriate layered-FFT transformation steps to the received samples so that the above mentioned different components of the received symbols, which have different delays or different Doppler shifts, are isolated, and their delays and Doppler shifts may thus be properly and coherently compensated. Data symbols transmitted in the delay-Doppler domain thus get the full diversity gain of the channel. This property of the delay-Doppler domain makes data transmission and detection in it particularly suited to high-mobility scenarios.

Another conventional transmission scheme is orthogonal time-frequency space (OTFS) modulation, in which the data symbols are transmitted and detected in the delay-Doppler domain, e.g., by using the appropriate layered FFT transceiver structure. In principle, OTFS may thus achieve a better reliability performance than A-OFDM or OFDM, for instance, due to its use of the delay-Doppler domain. However, using OTFS may require a relatively large number of null or guard symbols for separating the data symbols destined to or originating from different terminals or for those data symbols from pilot symbols. The number of the guard symbols, which represents an overhead to data transmission and needs to be reduced, increases either with the maximum delay spread or with the maximum Doppler frequency spread of the corresponding wireless transmission channels or with both.

It is thus generally desirable to design new waveforms that outperform the conventional waveforms in terms of reliability, achievable data rate, or latency, in particular on channels with a large Doppler frequency spread.

SUMMARY

In view of the above-mentioned problems and disadvantages, embodiments of the present disclosure aim to improve conventional transmitter devices, receiver devices and methods for wireless communication systems. An objective is to provide a transmit signal with a waveform that outperforms the conventionally used waveforms in terms of reliability, achievable data rate or latency. In particular, the new waveform should outperform on channels with a large Doppler frequency spread.

In particular, the transmitter device, the receiver device, and the methods of the present disclosure may use a layered FFT modulation, for example, a linearly pre-coded layered FFT (LP-LFFT) modulation. Further, by using the layered FFT, the transmitter device, the receiver device, and the methods of the present disclosure may perform one or more operations, by which a number of symbols may be arranged in a two-dimensional array, and an FFT algorithm may further be applied, e.g. repeatedly, to each vector of one of these two dimensions. Moreover, when using the linear precoding, the vectors of symbols constituting one or both dimensions of the two-dimensional array of symbols are obtained by a linear operation, i.e., a multiplication with a matrix, which is applied to a similar number of vectors of data symbols. The linear precoding may be done such that the LP-LFFT transmits data symbols in the delay-Doppler domain, e.g., for the sake of high diversity gains on high-mobility links, while at the same time creating an intermediate domain, i.e., an intermediate step in signal generation at the side of the transmitter device or in signal detection at the receiver device, with some desired properties. For example, one such desired property is to make the relation between the symbols of this intermediate step at the side of the receiver device and the corresponding symbols at the transmitter device resemble the equivalent relation experienced by frequency-domain symbols in systems transmitting and detecting data in the frequency domain, such as the OFDM, because fewer guard symbols are typically needed in the frequency-domain compared to the delay-Doppler domain to keep data/pilot interference and multi-user interference low. Moreover, it may be possible to choose the linear precoding in such a way that it yields this equivalent frequency-domain property, and the symbols corresponding to the intermediate step may be referred to as symbols belonging to an intermediate frequency-domain. Furthermore, it may be possible to insert the guard symbols in the intermediate frequency-domain to keep the overhead to a lower level (e.g., to a minimum level), while data symbols are transmitted and received in the delay-Doppler domain to achieve better reliability, for example, due to the diversity offered by the latter domain. The transmitter device, the receiver device, and the methods of the present disclosure may achieve a higher spectral efficiency and/or a better reliability, for example, by using fewer guard symbols (overhead) for both pilot or data multiplexing and for multiple-access purposes. Moreover, these performance gains can be achieved with faster-converging detection algorithms.

A first aspect of the present disclosure provides a transmitter device for a wireless communication system, the transmitter device being configured to obtain a plurality of first data symbol matrices in a delay-Doppler domain (which can also be referred to as Doppler-delay domain) for a plurality of users by arranging, for each user u of the plurality of users, data symbols of the user u in a first data symbol matrix having a form of $M_u \times N$, M_u being a number of rows specific to the user u, where $M_u > 1$, and N being a number of columns, where $N \geq 1$, obtain a plurality of second data symbol matrices in an intermediate-frequency domain for the plurality of users (e.g., using linear precoding) by performing, for each user u of the plurality of users, a M_u-point Fast Fourier Transform (FFT) operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of $M_u \times N$, obtain an aggregated matrix in the intermediate-frequency domain for the plurality of users by concatenating the N columns of each of the plurality of second data symbol matrices in the intermediate-frequency domain, the aggregated matrix having a form of $M \times N$, M being a number of rows, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of second data symbol matrices for the plurality of users.

In particular, the transmitter device may produce the transmit signal (e.g., having a new waveform) from the plurality of second data symbol matrices in the intermediate-frequency domain, e.g., by using a layered IFFT scheme, and the aggregated matrix in the intermediate-frequency domain to form a transmit signal. A layered-IFFT (or a layered-FFT) is a transformation applied to a vector of data symbols by rearranging the entries in a two-dimensional array and applying an IFFT transformation (or an FFT transformation) repeatedly to each row or to each column or to each row and to each column (in one order or another) of this array.

The present disclosure is not limited to a specific layered IFFT modulation scheme. For example, the steps performed at the transmitter device of the first aspect following the linear precoding and the intermediate-frequency domain steps may be based on an A-OFDM transmitter, an OTFS scheme, etc., without limiting the present disclosure.

The transmitter device of the first aspect may produce the transmit signal (e.g., having a new waveform) based on a linearly precoded layered IFFT scheme that may outperform the conventionally used transmit signals (waveforms) in terms of reliability, achievable data rate or latency. In particular, the transmitter device may outperform on channels with large Doppler frequency spread. For example, the transmitter device may enable a low-overhead multiple access for the layered-FFT-based wireless communication systems. Moreover, the transmitter device may enable transforming the data symbols of different users (data symbol matrices of different users) to the intermediate-frequency domain. Further, operating pilot insertion, multi-user guard symbols insertion, and channel estimation in the intermediate-frequency domain may provide a lower overhead of the guard symbols, which may increase the reliability or latency of the data rate.

In some embodiments, a precoding step, in particular a precoding step with low-computational complexity, may be used that may establish the intermediate-frequency domain.

In particular, the transmitter device may perform the M_u-point FFT or IFFT to pass from the M_u data symbols per column of the $M_u \times N$ first data symbol matrix in the delay-Doppler domain to the M_u symbols per column of the $M_u \times N$ second data symbol matrix in the intermediate-frequency domain.

In an implementation form of the first aspect, the transmitter device is further configured to insert guard symbols into the aggregated matrix in the intermediate-frequency domain, wherein the guard symbols are inserted between the concatenated N columns of each of the plurality of second data symbol matrices.

In a further implementation form of the first aspect, the transmitter device is further configured to insert channel estimation pilot symbols into one or more columns of the first data symbol matrix in the delay-Doppler domain at first positions known to a receiver device before obtaining the plurality of second data symbol matrices, or insert channel estimation pilot symbols into one or more columns of the second data symbol matrix in the intermediate frequency-domain at second positions known to the receiver device before obtaining the aggregated matrix in the intermediate-frequency domain.

For example, in some embodiments, a pilot symbol insertion (e.g., by the transmitter device) and a channel estimation operation (e.g., at a receiver device of a transceiver) may be performed in the intermediate-frequency domain based on pilot symbols inserted at the edges of each of the blocks of symbols belonging to the different users u in each column of the aggregated matrix. Performing these operations in this intermediate-frequency domain (instead of performing it in the delay-Doppler domain as in some conventional devices) may provide an advantage of requiring a relatively low overhead of guard symbols.

In a further implementation form of the first aspect, the transmitter device is further configured to obtain a phase-weighted aggregated matrix in the intermediate-frequency domain by performing a per-column phase-weighting operation on the aggregated matrix in the intermediate-frequency domain, wherein the per-column phase-weighting operation comprises multiplying each column of the aggregated matrix in the intermediate-frequency domain with a phase factor weighting matrix.

In a further implementation form of the first aspect, the transmitter device is further configured to perform a M-point Inverse FFT (IFFT) operation on the obtained phase-weighted aggregated matrix in the intermediate-frequency domain to convert the phase-weighted aggregated matrix in the intermediate-frequency domain to a phase-weighted aggregated matrix in the delay-Doppler domain.

In particular, the transmitter device may perform the M-point IFFT operation repeatedly on the columns of the obtained phase-weighted aggregated matrix in the intermediate-frequency domain.

In a further implementation form of the first aspect, the transmitter device is further configured to obtain a signal in the delay-Doppler domain based on the phase-weighted aggregated matrix in the delay-Doppler domain, and perform an N-point IFFT operation on the signal in the delay-Doppler domain to convert the signal in the delay-Doppler domain to a signal in a time domain, wherein the signal in the time domain includes a number of N×M symbols.

In a further implementation form of the first aspect, the transmitter device is further configured to perform a quadratic-phase (i.e., chirp) windowing procedure by multiplying the signal in the time domain with a set of window coefficients computed based on a delay-Doppler profile of a wireless communication channel of the wireless communication system, and add a chirp-periodic prefix at a beginning of the signal resulting from the quadratic-phase windowing procedure in the time domain.

In particular, performing the chirp windowing based on the delay-Doppler profile of the wireless communication channel may allow reducing multi-user interference and pilot/data interference in the intermediate frequency domain at the receiver device.

In a further implementation form of the first aspect, the transmitter device is further configured to receive a feedback message from the receiver device, the feedback message being indicative of CSI estimated by the receiver device based on the channel estimation pilot symbols inserted in the delay-Doppler domain or based on the channel estimation pilot symbols inserted in the intermediate-frequency domain.

A second aspect of the disclosure provides a receiver device for a wireless communication system, the receiver device being configured to obtain an aggregated matrix in an intermediate-frequency domain for a plurality of users based on a signal received in a time domain from a transmitter device, the aggregated matrix in the intermediate-frequency domain having a form of M×N, M being a number of rows, where M>1, and N being a number of columns, where N≥1, obtain a plurality of first data symbol matrices in the intermediate-frequency domain for the plurality of users by deconcatenating the N columns of the aggregated matrix in the intermediate-frequency domain, each first data symbol matrix having a form of M_u×N, M_u being a number of rows specific to a user u of the plurality of users, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of first data symbol matrices for the plurality of users, and obtain a plurality of second data symbol matrices in a delay-Doppler domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point Inverse Fast Fourier Transform (IFFT) operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of M_u×N.

In particular, the received signal may designate the symbols received by the receiver device before any processing.

In an implementation form of the second aspect, the receiver device is further configured to obtain a second signal in the time domain by discarding from the signal received in the time domain at least one prefix inserted at the transmitter device, and multiplying the signal received in the time domain with a set of window coefficients computed based on a delay-Doppler profile of a wireless communication channel of the wireless communication system.

In particular, the set of window coefficients computed based on the delay-Doppler profile of the wireless communication channel may comprise at least one of quadratic phase window coefficients and chirp window coefficients.

In a further implementation form of the second aspect, the receiver device is further configured to obtain a signal in the delay-Doppler domain by performing an N-point FFT operation on the second signal in the time domain.

In particular, the receiver device may obtain the signal in the delay-Doppler domain by performing a layered FFT operation on the second signal in the time domain, for example, by arranging the NM samples of this second signal in a M×N matrix and by repeatedly applying an N-point FFT operation on the rows of this matrix.

In a further implementation form of the second aspect, the receiver device is further configured to obtain a phase-weighted aggregated matrix in the delay-Doppler domain based on the signal in the delay-Doppler domain, and perform an M-point FFT operation on the phase-weighted aggregated matrix in the delay-Doppler domain to convert the phase weighted aggregated matrix in the delay-Doppler domain to a phase-weighted aggregated matrix in the intermediate-frequency domain.

In particular, the receiver device may repeatedly perform the M-point FFT operation on the columns of the phase-weighted aggregated matrix in the delay-Doppler domain.

In a further implementation form of the second aspect, the receiver device is further configured to obtain the aggregated matrix in the intermediate-frequency domain by performing a per-column phase-weighting operation on the phase-weighted aggregated matrix in the intermediate-frequency domain, wherein the per-column phase-weighting operation comprises multiplying each column of the phase-weighted aggregated matrix in the intermediated frequency domain with a diagonal phase-weighting matrix.

In a further implementation form of the second aspect, the receiver device is further configured to extract guard symbols from the N columns of the aggregated matrix in the intermediate-frequency domain, and obtain the plurality of first data symbol matrices in the intermediate-frequency

domain by deconcatenating the N columns of the aggregated matrix in the intermediate-frequency domain.

For example, the receiver device may extract from each column of the resulting phase-weighted aggregated matrix the M_u symbols belonging to user u in addition to the symbols received on the positions of the guard symbols. The extracting may be based on discarding the symbols occupying the entries of these columns that belong to other users' symbols and to their guard bands.

Furthermore, the receiver device may use the overlap-add operation comprising adding the symbols of each column received on the positions of the guard band, and located on each end of the non-guard symbols of the same column, to the same number of non-guard symbols that is located at the opposite end. Moreover, the receiver device performs the M_u-point IFFT operation on the obtained symbols for a transformation into a delay-Doppler domain.

In a further implementation form of the second aspect, the aggregated matrix in the intermediate-frequency domain further includes channel estimation pilot symbols inserted at the transmitter device in one or more columns.

In a further implementation form of the second aspect, the receiver device is further configured to estimate CSI based on the channel estimation pilot symbols in the delay-Doppler domain or in the intermediate-frequency domain.

In a further implementation form of the second aspect, the receiver device is further configured to send a feedback message to the transmitter device, the feedback message being indicative of the estimated CSI.

For example, in some embodiments, a signaling procedure and a procedure of sending feedback messages may be provided. The new signaling messages may be used in some embodiments of the disclosure to convey to the receiver device the exact data and pilot configuration and the windowing method that has been selected by the transmitter device among the possible windowing methods.

In some embodiments, the feedback messages may be used to convey to the transmitter device the CSI that has been calculated by the receiver device. For example, the receiver device may calculate the CSI based on the pilots that are inserted by the transmitter device in the intermediate-frequency domain.

A third aspect of the disclosure provides a method for a transmitter device, the method comprising obtaining a plurality of first data symbol matrices in a delay-Doppler domain for a plurality of users by arranging, for each user u of the plurality of users, data symbols of the user u in a first data symbol matrix having a form of $M_u \times N$, M_u being a number of rows specific to the user u, where $M_u > 1$, and N being a number of columns, where N **1**, obtaining a plurality of second data symbol matrices in an intermediate-frequency domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point Fast Fourier Transform (FFT) operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of $M_u \times N$, obtaining an aggregated matrix in the intermediate-frequency domain for the plurality of users by concatenating the N columns of each of the plurality of second data symbol matrices in the intermediate-frequency domain, the aggregated matrix having a form of M×N, M being a number of rows, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of second data symbol matrices for the plurality of users.

In an implementation form of the third aspect, the method further comprises inserting guard symbols into the aggregated matrix in the intermediate-frequency domain, wherein the guard symbols are inserted between the concatenated N columns of each of the plurality of second data symbol matrices.

In a further implementation form of the third aspect, the method further comprises inserting channel estimation pilot symbols into one or more columns of the first data symbol matrix in the delay-Doppler domain at first positions known to a receiver device before obtaining the plurality of second data symbol matrices, or inserting channel estimation pilot symbols into one or more columns of the second data symbol matrix in the intermediate frequency-domain at second positions known to the receiver device before obtaining the aggregated matrix in the intermediate-frequency domain.

In a further implementation form of the third aspect, the method further comprises obtaining a phase-weighted aggregated matrix in the intermediate-frequency domain by performing a per-column phase-weighting operation on the aggregated matrix in the intermediate-frequency domain, wherein the per-column phase-weighting operation comprises multiplying each column of the aggregated matrix in the intermediate-frequency domain with a phase factor weighting matrix.

In a further implementation form of the third aspect, the method further comprises performing a M-point IFFT operation on the obtained phase-weighted aggregated matrix in the intermediate-frequency domain to convert the phase-weighted aggregated matrix in the intermediate-frequency domain to a phase-weighted aggregated matrix in the delay-Doppler domain.

In a further implementation form of the third aspect, the method further comprises obtaining a signal in the delay-Doppler domain based on the phase-weighted aggregated matrix in the delay-Doppler domain, and performing an N-point IFFT operation on the signal in the delay-Doppler domain to convert the signal in the delay-Doppler domain to a signal in a time domain, wherein the signal in the time domain includes a number of N×M symbols.

In a further implementation form of the third aspect, the method further comprises performing a quadratic-phase windowing procedure by multiplying the signal in the time domain with a set of window coefficients computed based on a delay-Doppler profile of a wireless communication channel of the wireless communication system, and adding a chirp-periodic prefix at a beginning of the signal resulting from the quadratic-phase windowing procedure in the time domain.

In a further implementation form of the third aspect, the method further comprises receiving a feedback message from the receiver device, the feedback message being indicative of CSI estimated by the receiver device based on the channel estimation pilot symbols inserted in the delay-Doppler domain or based on the channel estimation pilot symbols inserted in the intermediate-frequency domain.

The method of the third aspect achieves the advantages and effects described for the transmitter device of the first aspect.

A fourth aspect of the disclosure provides a method for a receiver device, the method comprising obtaining an aggregated matrix in an intermediate-frequency domain for a plurality of users based on a signal received in a time domain from a transmitter device, the aggregated matrix in the intermediate-frequency domain having a form of M×N, M being a number of rows, where M>1, and N being a number of columns, where N **1**, obtaining a plurality of first data symbol matrices in the intermediate-frequency domain for the plurality of users by deconcatenating the N columns of

the aggregated matrix in the intermediate-frequency domain, each first data symbol matrix having a form of $M_u \times N$, M_u being a number of rows specific to a user u of the plurality of users, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of first data symbol matrices for the plurality of users, and obtaining a plurality of second data symbol matrices in a delay-Doppler domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point Inverse Fast Fourier Transform (IFFT) operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of $M_u \times N$.

In an implementation form of the fourth aspect, the method further comprises obtaining a second signal in the time domain by discarding from the signal received in the time domain at least one prefix inserted at the transmitter device, and multiplying the signal received in the time domain with a set of window coefficients computed based on a delay-Doppler profile of a wireless communication channel of the wireless communication system.

In a further implementation form of the fourth aspect, the method further comprises obtaining a signal in the delay-Doppler domain by performing an N-point FFT operation on the second signal in the time domain.

In a further implementation form of the fourth aspect, the method further comprises obtaining a phase-weighted aggregated matrix in the delay-Doppler domain based on the signal in the delay-Doppler domain, and performing an M-point FFT operation on the phase-weighted aggregated matrix in the delay-Doppler domain to convert the phase-weighted aggregated matrix in the delay-Doppler domain to a phase-weighted aggregated matrix in the intermediate-frequency domain.

In a further implementation form of the fourth aspect, the method further comprises obtaining the aggregated matrix in the intermediate-frequency domain by performing a per-column phase-weighting operation on the phase-weighted aggregated matrix in the intermediate-frequency domain, wherein the per-column phase-weighting operation comprises multiplying each column of the phase-weighted aggregated matrix in the intermediated frequency domain with a diagonal phase-weighting matrix.

In a further implementation form of the fourth aspect, the method further comprises extracting guard symbols from the N columns of the aggregated matrix in the intermediate-frequency domain, and obtaining the plurality of first data symbol matrices in the intermediate-frequency domain by deconcatenating the N columns of the aggregated matrix in the intermediate-frequency domain.

In a further implementation form of the fourth aspect, the aggregated matrix in the intermediate-frequency domain further includes channel estimation pilot symbols inserted at the transmitter device in one or more columns.

In a further implementation form of the fourth aspect, the method further comprises estimating CSI based on the channel estimation pilot symbols in the delay-Doppler domain or in the intermediate-frequency domain.

In a further implementation form of the fourth aspect, the method further comprises sending a feedback message to the transmitter device, the feedback message being indicative of the estimated CSI.

The method of the fourth aspect achieves the advantages and effects described for the receiver device of the first aspect.

A fifth aspect of the present disclosure provides a computer program comprising a program code for performing the method according to the third aspect or fourth aspect or any of their implementation forms.

A sixth aspect of the present disclosure provides a non-transitory storage medium storing executable program code which, when executed by a processor, causes the method according to the third aspect or fourth aspect or any of their implementation forms to be performed.

The devices, elements, units and means described in the present application can be implemented in software or hardware elements or any kind of combination thereof. The steps which are performed by the various entities described in the present application, as well as the functionalities described to be performed by the various entities, are intended to mean that the respective entity is adapted to or configured to perform the respective steps and functionalities. Even if, in the following description of specific embodiments, a specific functionality or step to be performed by external entities is not reflected in the description of a specific detailed element of that entity which performs that specific step or functionality, it should be clear for a skilled person that these methods and functionalities can be implemented in respective software or hardware elements, or any kind of combination thereof.

BRIEF DESCRIPTION OF DRAWINGS

The above described aspects and implementation forms will be explained in the following description of specific embodiments in relation to the enclosed drawings, in which:

FIG. **1** depicts a schematic view of a transmitter device for a wireless communication system, according to an embodiment of the disclosure;

FIG. **2** depicts a schematic view of a receiver device for a wireless communication system, according to an embodiment of the disclosure;

FIGS. **3**A and **3**B depict a schematic view of a transmitter device for a wireless communication system, according to an embodiment of the disclosure;

FIGS. **4**A and **4**B depict a schematic view of a receiver device for a wireless communication system, according to an embodiment of the disclosure;

FIG. **5** depicts a schematic view illustrating the transmitter device inserting pilot symbols in the delay-Doppler domain;

FIG. **6** depicts a schematic view illustrating the receiver device performing a channel estimation in the delay-Doppler domain;

FIG. **7**A depicts a schematic view illustrating the transmitter device performing pilot insertion in the intermediate-frequency domain, with one pilot block per data block for interpolation at the receiver side;

FIG. **7**B depicts a schematic view of a diagram illustrating the transmitter device performing pilot insertion in the intermediate-frequency domain, with two pilot blocks for interpolation at the receiver side;

FIG. **8**A depicts a schematic view illustrating the receiver device performing channel estimation in the intermediate-frequency domain, without interpolation;

FIG. **8**B depicts a schematic view illustrating the receiver device performing channel estimation in the intermediate-frequency domain, with interpolation;

FIG. **9** depicts a schematic view of a block diagram of a linearly pre-coded layered FFT (LP-LFFT) transmitter device with rectangular windowing and cyclic prefix (CP) insertion, according to an embodiment of the disclosure;

FIGS. **10**A and **10**B depict a schematic view of a block diagram of a LP-LFFT receiver device, in case a rectangular

windowing is used at the transmitter device, according to an embodiment of the disclosure;

FIGS. **11**A and **11**B depict a schematic view of a block diagram of a LP-LFFT transmitter device with discrete prolate spheroidal sequence (DPSS) windowing and CP insertion, according to an embodiment of the disclosure;

FIGS. **12**A and **12**B depict a schematic view of a block diagram of a LP-LFFT receiver device, in case a DPSS windowing is used at the transmitter device, according to an embodiment of the disclosure;

FIGS. **13**A and **13**B depict a schematic view of a block diagram of a LP-LFFT transmitter device with a chirp-coefficient windowing and chirp-periodic prefix insertion, according to an embodiment of the disclosure;

FIGS. **14**A and **14**B depict a schematic view of a block diagram of a LP-LFFT receiver device in the case of chirp-coefficient windowing, according to an embodiment of the disclosure;

FIG. **15** depicts a flowchart of a method for a transmitter device, according to an embodiment of the disclosure; and

FIG. **16** depicts a flowchart of a method for a receiver device, according to an embodiment of the disclosure.

DETAILED DESCRIPTION OF EMBODIMENTS

FIG. **1** depicts a schematic view of a transmitter device **100** for a wireless communication system **1**, according to an embodiment of the disclosure.

The transmitter device **100** may comprise a first encoder **101**, a M_u-point FFT module **102**, and a second encoder **103**. The first encoder **101** and the second encoder **103** may be similar or identical. Moreover, the first encoder **101** and the second encoder **103** may perform similar or identical functions, without limiting the present disclosure.

The first encoder **101** of the transmitter device **100** may obtain a plurality of first data symbol matrices **111**, **112**, **113** (which are not structural elements of the transmitter device **100**) in a delay-Doppler domain for a plurality of users. For the sake of simplicity, in the discussion of FIG. **1**, it is assumed that there are three users.

For example, the first encoder **101** of the transmitter device **100** may obtain the first data symbol matrix **111** for a first user by arranging data symbols of the first user in the first data symbol matrix **111** having a form of $M_u \times N$. Thereby, M_u is a number of rows specific to the first user, where $M_u > 1$, and N is a number of columns, where N **1**. Likewise, the first encoder **101** may obtain the first data symbol matrix **112** for a second user by arranging data symbols of the second user in the first data symbol matrix **112** having a form of $M_u \times N$, and may obtain the first data symbol matrix **113** for a third user by arranging data symbols of the third user in the first data symbol matrix **113** having a form of $M_u \times N$.

Thereby, at least one of guard symbols and channel estimation pilot symbols may be inserted between the data symbols, as described below in detail.

Moreover, the M_u-point FFT module **102** of the transmitter device **100** may comprise a number of instances that may be equal in number to the number of users. That is, with U being the number of users, the M_u-point FFT module **102** may comprise U instances. For example, in FIG. **1**, three instances of the M_u-point FFT module **102** are illustrated as a first instance **120***a*, a second instance **120***b*, and a third instance **120***c* for the three users, respectively.

The M_u-point FFT module **102** of the transmitter device **100** may obtain a plurality of second data symbol matrices **121**, **122**, **123** (which are not structural elements of the transmitter device **100**) in an intermediate-frequency domain for the plurality of users.

The first instance **120***a* of the M_u-point FFT module **102** of the transmitter device **100** may perform, for the first user, a M_u-point FFT operation on the first data symbol matrix **111** of the first user, and obtain the second data symbol matrix **121** of the first user. The second data symbol matrix **121** of the first user may have the form of $M_u \times N$. Further, the second instance **120***b* may perform, for the second user, a M_u-point FFT operation on the first data symbol matrix **112** of the second user, and obtain the second data symbol matrix **122** of the second user. The second data symbol matrix **122** of the second user may have the form of $M_u \times N$. Finally, the third instance **120***c* may perform, for the third user, a M_u-point FFT operation on the first data symbol matrix **113** of the third user, and obtain the second data symbol matrix **123** of the third user. The second data symbol matrix **123** of the third user may have the form of $M_u \times N$.

Moreover, the transmitter device **100** may further comprise the second encoder **103**. The second encoder **103** may obtain an aggregated matrix **130** (which is not a structural element of the transmitter device **100**) in the intermediate-frequency domain for the plurality of users. For example, the second encoder **103** may concatenate the N columns of each of the plurality of second data symbol matrices **121**, **122**, **123** in the intermediate-frequency domain, and obtain the aggregated matrix **130**. The aggregated matrix **130** may have a form of M×N, where M is a number of rows. Moreover, M is greater than a sum of the respective numbers of rows M_u of the plurality of second data symbol matrices **121**, **122**, **123** for the plurality of users.

Moreover, the aggregated matrix **130** in the intermediate-frequency domain may further be provided with guard symbols, with pilot symbols, and with other intermediate-frequency domain symbols belonging to other transmitter devices or destined to other receiver devices.

The transmitter device **100** may comprise a processing circuitry (not shown in FIG. **1**) configured to perform, conduct or initiate the various operations of the transmitter device **100** described herein. The processing circuitry may comprise hardware and software. The hardware may comprise analog circuitry or digital circuitry, or both analog and digital circuitry. The digital circuitry may comprise components such as application-specific integrated circuits (ASICs), field-programmable arrays (FPGAs), digital signal processors (DSPs), or multi-purpose processors. In one embodiment, the processing circuitry comprises one or more processors and a non-transitory memory connected to the one or more processors. The non-transitory memory may carry executable program code which, when executed by the one or more processors, causes the transmitter device **100** to perform, conduct or initiate the operations or methods described herein.

FIG. **2** depicts a schematic view of a receiver device **200** for a wireless communication system **1**, according to an embodiment of the disclosure.

The receiver device **200** may comprise a first decoder **203**, a M_u-point IFFT module **202**, and a second decoder **201**.

The first decoder **203** and the second decoder **201** may be similar or identical. Moreover, the first decoder **203** and the second decoder **201** may perform similar or identical functions, without limiting the present disclosure.

The first decoder **203** of the receiver device **200** may obtain an aggregated matrix **230** (which is not a structural element of the receiver device **200**) in an intermediate-frequency domain for a plurality of users based on a signal **110** received in a time domain from a transmitter device **100**.

For the sake of simplicity, in the discussion of FIG. **2**, it is again assumed that there are three users.

The aggregated matrix **230** in the intermediate-frequency domain has a form of M×N, where M is a number of rows, M>1, and N is a number of columns, N≥1.

Moreover, the second decoder **201** of the receiver device **200** may obtain a plurality of first data symbol matrices **221**, **222**, **223** (which are not structural elements of the receiver device **200**) in the intermediate-frequency domain for the plurality of users.

For example, the second decoder **201** of the receiver device **200** may deconcatenate the N columns of the aggregated matrix **230** in the intermediate-frequency domain, and obtain the first data symbol matrix **221** for the first user. Further, the second decoder **201** may deconcatenate the N columns of the aggregated matrix **230** in the intermediate-frequency domain, and obtain the first data symbol matrix **222** for the second user. Moreover, the second decoder **201** may deconcatenate the N columns of the aggregated matrix **230** in the intermediate-frequency domain, and obtain the first data symbol matrix **223** for the third user.

The plurality of first data symbol matrices **221**, **222**, **223** may each have a form of M_u×N, where M_u is a number of rows specific to the user u associated with the respective first data symbol matrix, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of first data symbol matrices **221**, **222**, **223** for the plurality of users.

Moreover, the M_u-point IFFT module **202** of the receiver device **200** may comprise a number of instances that may be equal to the number of the users. That is, with U being the number of users, the M_u-point IFFT module **202** may comprise U instances. For example, in the embodiment of FIG. **2**, a first instance **220***a*, a second instance **220***b*, and a third instance **220***c* of the M_u-point IFFT module **202** are illustrated for the three users, respectively.

The M_u-point IFFT module **202** of the receiver device **200** may obtain a plurality of second data symbol matrices **211**, **212**, **213** (which are not structural elements of the receiver device **200**) in a delay-Doppler domain for the plurality of users.

For example, the first instance **220***a* of the M_u-point IFFT module **202** of the receiver device **200** may perform, for the first user, a M_u-point IFFT operation on the first data symbol matrix **221** of the first user, and obtain the second data symbol matrix **211** of the first user. The plurality of second data symbols matrices may have the form of M_u×N. Further, the second instance **220***b* may perform, for the second user, a M_u-point IFFT operation on the first data symbol matrix **222** of the second user, and obtain the second data symbol matrix **212** of the second user. Moreover, the third instance **220***c* may perform, for the third user, a M_u-point IFFT operation on the first data symbol matrix **223** of the third user, and obtain the second data symbol matrix **213** of the third user.

The receiver device **200** may comprise a processing circuitry (not shown in FIG. **2**) configured to perform, conduct or initiate the various operations of the receiver device **200** described herein. The processing circuitry may comprise hardware and software. The hardware may comprise analog circuitry or digital circuitry, or both analog and digital circuitry. The digital circuitry may comprise components such as application-specific integrated circuits (ASICs), field-programmable arrays (FPGAs), digital signal processors (DSPs), or multi-purpose processors. In one embodiment, the processing circuitry comprises one or more processors and a non-transitory memory connected to the one or more processors. The non-transitory memory may carry executable program code which, when executed by the one or more processors, causes the receiver device **200** to perform, conduct or initiate the operations or methods described herein.

FIGS. **3**A and **3**B depict a schematic view of a transmitter device **100** for a wireless communication system **1** according to an embodiment of the disclosure, which builds on the embodiment shown in FIG. **1**. In particular, FIGS. **3**A and **3**B illustrate details of the transmitter device **100** for a specific user u of the plurality of users (wherein u is in a range of 1 to U, with U being the number of users).

In particular, the transmitter device **100** of FIGS. **3**A and **3**B further comprises (in addition to the elements of the transmitter device **100** shown in FIG. **1**) a phase-weighting module **301**, an M-IFFT module **302**, a column-wise to row-wise module **303**, a N-IFFT module **304**, a row-wise to column-wise module **305**, a successive M-long windowing module **306**, a prefix addition module **307**, and a parallel-to-series module **308**.

The transmitter device **100** may obtain a number of $NM_{u\text{-}1}$ data symbols, which are denoted $s_{u,0}, \ldots, s_{u,N\,M_{u\text{-}1}}$ and are destined to the user u. The data symbols carry data, i.e. information, which is to be transmitted to the user u by the transmitting device **100**. The data symbols may have been generated by mapping the information to be transmitted to the user u (e.g., a certain sequence of bits) onto a discrete alphabet comprising symbols, e.g., onto a symbol constellation.

The transmitter device **100** may further arrange the $NM_{u\text{-}1}$ data symbols $s_{u,0}, \ldots, s_{u,N\,M_{u\text{-}1}}$ of the user u into a first data symbol matrix of the user u in the delay-Doppler domain. For example as shown, the user u may be the first user mentioned above with respect to FIG. **1**, and the data symbols may be arranged into the first data symbol matrix **111** of the first user having the form of M_u×N, as already shown in FIG. **1**. The first data symbol matrix **111** may then be provided as an input to the M_u-point FFT module **102**, in particular, to the instance **120***a* that is associated with the first user.

Accordingly, the transmitter device **100** of FIGS. **3**A and **3**B comprises the M_u-point FFT module **102**, which may have U instances, wherein U is the number of users, i.e. one instance per user (only the instance **120***a* of the first user is shown in FIGS. **3**A and **3**B). For example, it may comprise the three instances **120***a*, **120***b*, **120***c* for the three users exemplarily shown in FIG. **1**. The M_u-point FFT module **102** may apply, using a different instance per user, a M_u-point FFT operation on the first data symbol matrix of each user. In particular, each of the instances of the M_u-point FFT module **102** may apply a M_u-point FFT operation on one of the first data symbol matrices. Thereby, the module **102** may obtain U second data symbol matrices, e.g., the three second data symbol matrices **121**, **122**, **123** shown in FIG. **1**.

In particular, as shown in FIGS. **3**A and **3**B where the user u is exemplarily the first user, each column of the N columns of the first data symbol matrix **111** of the first user may be provided to a different block **320** of the instance **120***a* of the M_u-point FFT module **102**. The size of each block **320** may be $M_u \leq M$, i.e., each block **320** is able to process one entire column spanning all the M_u rows of the first data symbol matrix **111**, wherein $\Sigma_{u=1}^{U} M_u \leq M$. Each of the U instances of the M_u-point FFT module **102** may comprise N blocks **320** (one for each of the N columns of the respective first data symbol matrix), so that there may be a total number of N×U number of blocks **320** in the entire M_u-point FFT module **102**.

After the M_u-point FFT module **102**, the transmitter device **100** may further obtain the aggregated matrix **130** having the form of M×N. For example, the U second data symbol matrices, which are output from the U instances of the M_u-point FFT module **102**, may be concatenated with each other to form the aggregated matrix **130**. In particular, as shown in FIGS. **3**A and **3**B for the user u being exemplarily the first user, the N columns of the second data symbol matrix **121**, as output respectively from the N blocks **320** of the instance **210***a* of the M_u-point FFT module **102**, may be concatenated in the intermediate-frequency domain. This may be likewise done for the second data symbol matrix of each user. Thereby, a number of zero symbols or guard symbols may be inserted between the data symbols of the second data symbol matrices of the plurality of users, particularly, between the concatenated N columns of these second data symbol matrices. Thus, the data symbols belonging to different users in the aggregated matrix **130** may be separated by the inserted guard symbols.

Subsequently, the phase weighting module **301** of the transmitter device **100** may obtain a phase-weighted aggregated matrix in the intermediate-frequency domain. For example, the phase weighting module **301** of the transmitter device **100** may perform a per-column phase-weighting operation on the aggregated matrix **130** in the intermediate-frequency domain to obtain the phase-weighted aggregated matrix.

For instance, the phase weighting module **301** of the transmitter device **100** may multiply each column of the aggregated matrix **130** in the intermediate-frequency domain with a phase factor weighting matrix to perform the per-column phase-weighting operation.

For example, the phase factor weighting matrix for the n^{th} column of the aggregated matrix **130** (where $0 \le n \le N-1$) may be as follows:

$$\Phi_n = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & e^{\iota 2\pi \frac{n}{N}} & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & e^{\iota 2\pi \frac{n(M-1)}{N}} \end{bmatrix}$$

That is, the n^{th} column of the aggregated matrix **130** may be multiplied with the above matrix Φ_n. This particular weighting matrix has advantages in limiting multi-user interference and data/pilot interference in the intermediate frequency domain of the receiver device.

The transmitter device **100** further comprises an M-IFFT module **302**, which may have N instances per user. The M-IFFT module **302** of the transmitter device **100** may repeatedly perform an M-point IFFT operation on each column of the phase-weighted aggregated matrix in the intermediate-frequency domain, to convert the phase-weighted aggregated matrix in the intermediate-frequency domain to a phase-weighted aggregated matrix in the delay-Doppler domain.

The transmitter device **100** further comprises the column-wise to row-wise module **303**. The column-wise to row-wise module **303** may receive the phase-weighted aggregated matrix in the delay-Doppler domain output by the M-IFFT module **302**, and may obtain a signal in the delay-Doppler domain based on the phase-weighted aggregated matrix in the delay-Doppler domain. In particular, the column-wise to row-wise module **303** may rearrange the phase-weighted aggregated matrix into M blocks, each block being of size N, to obtain the signal in the delay-Doppler domain.

Moreover, the N-IFFT module **304** of the transmitter device **100** may repeatedly perform an N-point IFFT operation on each of the M blocks of the signal in the delay-Doppler domain to convert the signal in the delay-Doppler domain to a signal in a time domain. Thereby, the signal in the time domain includes a number of N×M symbols.

The transmitter device **100** further comprises the row-wise to column-wise module **305** that may rearrange the signal in the time domain.

The transmitter device **100** further comprises the successive N-long windowing module **306**. The successive M-long windowing module **306** may perform a quadratic-phase windowing procedure. For example, the successive M-long windowing module **306** may multiply the signal in the time domain received from the row-wise to column-wise module **305** with a set of chirp window coefficients computed based on a delay-Doppler profile of the wireless communication channel of the wireless communication system **1**.

The transmitter device **100** further comprises the prefix addition module **307** that may add a chirp-periodic prefix at a beginning of the signal resulting from the quadratic-phase windowing procedure in the time domain. The parallel-to-series module **308** may serialize the signal resulting from the prefix addition module **307**.

Notably, the present disclosure is not limited to a specific configuration of the modules **304** to **308** of the transmitter device **100**. For example, the modules **304** to **308** may be any known modules for delay-Doppler domain to time-domain transformation, e.g., of a conventional layered-FFT transmitter, e.g., an OTFS transmitter.

FIGS. **4**A and **4**B depict a schematic view of a receiver device **200** for a wireless communication system **1** according to an embodiment of the disclosure, which builds on the embodiment shown in FIG. **2**. In particular, FIGS. **4**A and **4**B illustrate details of the receiver device **200** for a specific user u of the plurality of users (wherein u is in a range of 1 to U, with U being the number of users).

Generally, at the receiver device **200** operations inverse to the operations performed at the transmitter device **100**, as described above with respect to FIGS. **3**A and **3**B, may be carried out.

The receiver device **200** of FIGS. **4**A and **4**B further comprises (in addition to the elements of the receiver device **200** shown in FIG. **2**) a series-to-parallel module **401**, a prefix removal module **402**, a successive M-long windowing module **403**, a column-wise to row-wise module **404** and an N-FFT module **405** having N instances per user, a row-wise to column-wise module **406**, a M-FFT module **407** having N instances per user, and a phase weighting module **408**.

The receiver device **200** may receive a signal in a time domain **110** from the transmitter device **100**. The signal may comprise symbols (e.g., including data symbols, and guard symbols or pilot symbols). The series-to-parallel module **401** may parallelize the signal **110**. The parallelized signal in the time domain may be a vector comprising N×M number of symbols.

The prefix removal module **402** may discard, from the parallelized signal **110** in the time domain, at least one prefix inserted at the transmitter device **100**. For example, the prefix removal module **402** of the receiver device **200** may discard any prefix that has been inserted at the side of the transmitter device **100**.

Further, the successive M-long windowing module **403** may multiply the signal **110** received in the time domain from the prefix removal module **402** with a set of chirp window coefficients computed based on a delay-Doppler

profile of a wireless communication channel of the wireless communication system **1**, to obtain a second signal in the time domain.

The column-wise to row-wise module **404** of the receiver device **200** may further rearrange the symbols of the second signal in the time domain.

The N-FFT module **405** may perform an N-point FFT operation on the second signal in the time domain as received from the column-wise to row-wise module **404**. The N-FFT module **405** may accordingly output a signal in the delay-Doppler domain. The symbols of the signal in the delay-Doppler domain may then be rearranged in the row-wise to column-wise module **406**.

Notably, the present disclosure is not limited to a specific configuration of these modules **401** to **405** of the receiver device **200**. For example, the modules **401** to **405** may be any known modules for transforming time-domain signals of length M×N to delay-Doppler domain signals of M×N dimensions.

Subsequently, the receiver device **200** may obtain a phase-weighted aggregated matrix in the delay-Doppler domain based on the signal in the delay-Doppler domain received from the row-wise to column-wise module **406**. Furthermore, the M-FFT module **407** may perform an M-point FFT operation on the phase-weighted aggregated matrix in the delay-Doppler domain, to convert the phase weighted aggregated matrix in the delay-Doppler domain to a phase-weighted aggregated matrix in the intermediate-frequency domain.

The phase weighting module **408** of the receiver device **200** may then perform a per-column phase-weighting operation on the phase-weighted aggregated matrix in the intermediate-frequency domain, to obtain an aggregated matrix **230** in the intermediate-frequency domain. For example, the phase weighting module **408** of the receiver device **200** may multiply each column of the phase-weighted aggregated matrix in the intermediate-frequency domain with a diagonal phase-weighting matrix to perform the per-column phase weighting operation. For instance, it may multiply the n^{th} column (where $0 \le n \le N-1$) of the phase-weighted aggregated matrix with the inverse of the matrix Φ_n described above. The aggregated matrix **230** has a form of M×N.

Furthermore, the receiver device **200** may comprise the prefix-suffix overlap-add module **409**. The prefix-suffix overlap-add module **409** may obtain the plurality of first data symbol matrices for the plurality of users in the intermediate-frequency domain by deconcatenating the N columns of the aggregated matrix **230** in the intermediate-frequency domain. For instance, as shown in FIGS. **4**A and **4**B where the user u is exemplarily the first user mentioned above, the prefix-suffix overlap-add module **409** may obtain the first data symbol matrix **221** for the first user.

To this end, the prefix-suffix overlap-add module **409** may perform an overlap-add procedure on the aggregated matrix **230**. Thereby, it may extract guard symbols from the N columns of the aggregated matrix **230** in the intermediate-frequency domain. For instance, it may extract symbols in the aggregated matrix **230** on positions of a prefix guard band (e.g., guard symbols preceding the data symbols, which belong to the user u in the aggregated matrix **230**) and on the positions of a suffix guard band (e.g., guard symbols, which belong to the user u, following these data symbols in the aggregated matrix **230**) in each column of the aggregated matrix **230**. The symbols on the positions of the prefix guard band and suffix guard band may correspond to guard symbols inserted into the aggregated matrix **130** at the side of the transmitter device **100** between data symbols of the second data symbol matrix **121** belonging to the user u. The prefix-suffix overlap-add module **409** may add the symbol positions of the prefix guard band to symbols on the positions of the data symbols in the aggregated matrix **230** using the. The add-overlap procedure may be a conventional add-overlap procedure. The prefix-suffix overlap-add module **409** may perform the overlap-add procedure, before feeding the result thereof as an input to the M_u-point IFFT module **202**.

The M_u-point IFFT module **202** may perform, for each user u of the plurality of users, a M_u-point IFFT operation on the first data symbol matrix of the user u, to obtain the plurality of second data symbol matrices in the delay-Doppler domain. Thereby, a second data symbol matrix is obtained for each user u of the plurality of users. The M_u-point IFFT module **202** may comprise an instance for each user u, i.e., it may have U instances. For example, as shown in FIGS. **4**A and **4**B where the user u is exemplarily the first user, the instance **220***a* of the M-point IFFT module **202** associated with the first user may obtain the second data symbol matrix **211** of the first user from the first data symbol matrix **221** of the first user. Each instance of the M_u-point IFFT module **202**—like the shown instance **220***a* associated with the first user—may comprise N blocks **420**. As shown, each column of the N columns of the first data symbol matrix **221** of the first user may be provided to a different block **420** of the instance **220***a* of the M_u-point IFFT module **202**. The size of each block **420** may be $M_u \le M$, i.e. each block **420** is able to process one entire column spanning all the M_u rows of the first data symbol matrix **121**, wherein $\Sigma_{u=1}^{U} M_u \le M$. Notably, each of the U instances of the M_u-IFFT module **202** may comprise N blocks **420** (one for each of the N columns of the respective first data symbol matrix), so that there may be a total number of N×U number of blocks **420** in the entire M_u-IFFT module **202**.

FIG. **5** depicts a diagram illustrating an example of the transmitter device **100**, which builds on the transmitter device **100** shown in FIGS. **3**A and **3**B, the transmitter device **100** being configured to insert pilot symbols in the delay-Doppler domain. In particular, the transmitter device **100** may insert the pilot symbols into one or more columns of a first data symbol matrix (here of the first data symbol matrix **111** of the first user) in the delay-Doppler domain at first positions known to the receiver device **200**, before obtaining the plurality of second data symbol matrices.

In some embodiments, the transmitter device **100** may insert the pilot symbols to give the receiver device **200** the possibility to estimate the channel. These inserted channel estimation pilot symbols may be symbols that are known to the receiver device **200**, and are transmitted at positions within the resource grid, which are also known to the receiver device **200**.

As shown in FIG. **5**, the transmitter device **100** may comprise a pilot generation module **501** that may generate the pilot symbols to be inserted. The generated pilot symbols may then be inserted into, e.g., the first data symbol matrix **111**, particularly among the data symbols of that first data symbol matrix **111**, and may be surrounded by a determined number of guard symbols to prevent the data symbols and pilot symbols from interfering. The pilot symbols may be inserted at the input of the M_u-point FFT module **102** (e.g. as shown, at a block **320** of the instance **120***a* that is responsible for performing the M_u-point FFT operation on the first data symbol matrix **111** of the first user).

FIG. **6** depicts a schematic view of a diagram illustrating an example of a receiver device **200**, which builds on the

receiver device **200** shown in FIGS. **4**A and **4**B, configured to perform a corresponding channel estimation in the delay-Doppler domain.

FIG. **6** particularly illustrates the phase weighting module **408**, the prefix-suffix overlap-add module **409**, and a block **420** of an instance of the M_u-point IFFT module **202** of the receiver device **200**, which may be identical or similar to their corresponding modules discussed with respect to the receiver device of FIGS. **4**A and **4**B. Further, the receiver device **200** may comprise a channel estimation module **601** that may estimate the channel based on the pilot symbols inserted by the transmitter device **100** as discussed above.

Thereby, a subset of the guard symbols that is corrupted by interference with the data symbols may be discarded, and thus may not be used for channel estimation (as opposed to the subset of guard symbols not corrupted by such interferences but instead only containing a contribution from the pilot symbols after they passed through the wireless channel).

In some embodiments, it may be possible to decrease the guard symbol overhead, for example, by inserting the pilot symbols at the transmitter device **100** in the intermediate-frequency domain instead of the delay-Doppler domain. In particular, FIG. **7**A and FIG. **7**B illustrate two possibilities for inserting the pilot symbols in the intermediate-frequency domain.

FIG. **7**A depicts a schematic view of a diagram illustrating the transmitter device **100** performing the pilot insertion in the intermediate-frequency domain, with one pilot block per data block. The same blocks as in FIG. **5** are shown in FIG. **7**A and are labelled with the same reference signs. As it can be derived from FIG. **7**A, the pilot generation module **501** of the transmitter device **100** may again generate the pilot symbols. Further, one pilot symbol block per second data symbol matrix may be inserted, e.g. as shown into the second data symbol matrix **121** of the first user being the specific user u, which is output by the blocks **320** of the instance **120***a* of the M_u-point FFT module **102**. The transmitter device **100** is particularly configured to insert the pilot symbols into one or more columns (one column output per block **320** of the instance **120***a*) of the second data symbol matrix **121** in the intermediate frequency-domain at second positions known to the receiver device **200**, before obtaining the aggregated matrix **130** in the intermediate-frequency domain.

FIG. **7**B depicts a schematic view of a diagram illustrating the transmitter device **100** performing the pilot insertion in the intermediate-frequency domain like in FIG. **7**B, but with two pilot symbol blocks inserted into the second data symbol matrix **121** of the first user output by the blocks **320** of the instance **120***a* of the M_u-point FFT module **102**, before obtaining the aggregated matrix **130**. The pilot symbols may be used for interpolation-based channel estimation at the receiver side. The same blocks as in FIGS. **5** and **7**A are shown and are labelled with the same reference signs.

In some embodiments, the receiver device **200** may estimate the channel in the intermediate-frequency domain. FIG. **8**A and FIG. **8**B depict the corresponding channel estimation blocks at the receiver side.

FIG. **8**A depicts a schematic view of a diagram illustrating the receiver device **200** performing a channel estimation in the intermediate-frequency domain, and without an interpolation.

As it can be derived from FIG. **8**A, the channel estimation module **601** of the receiver device **200** may estimate the channel, and one pilot symbol block may be used for the estimation.

For example, the receiver device **200** may receive the signal **110** transmitted from the transmitter device **100**. As an example, the transmitter device **100** may have inserted the channel estimation pilot symbols, and optionally guard symbols surrounding the pilot symbols, into the columns of the second data symbol matrices in the intermediate frequency-domain at second positions known to the receiver device **200**, before having obtained the aggregated matrix **130** as described above. Based thereon, the transmitted device **100** may have generated the signal **110**. In the diagram of FIG. **8**A, it is particularly assumed that the transmitter device **100** inserted one pilot symbol block per second data symbol matrix (as shown in FIG. **7**A).

Further, the phase weighting module **408** of the receiver device **200** may perform a per-column phase factor weighting operation on the obtained phase-weighted aggregated matrix, and may further obtain (e.g., extract) the symbols received on the known positions of the channel estimation pilot symbols and optionally the interference-free guard symbols surrounding these symbols. Moreover, the channel estimation module **601** of the receiver device **200** may use the obtained symbols on the known positions of the channel estimation pilot symbols to estimate the channel. The present disclosure is not limited to a specific channel estimation procedure.

Furthermore, the prefix-suffix overlap-add module **409** may then remove, e.g., the added prefix guard symbols preceding the data symbols block, and the blocks **420** of the instances of the M_u-IFFT module **202** (e.g., at the instance **220***a* for the first user being the specific user u as shown) may perform a per-column IFFT modulation as described before.

FIG. **8**B depicts a schematic view of a diagram illustrating the receiver device **200** performing a channel estimation in the intermediate-frequency domain with an interpolation.

As it can be derived from FIG. **8**B, the channel estimation module **601** of the receiver device **200** may estimate the channel, wherein two pilot symbol blocks may be used.

The receiver device **200** of FIG. **8**B may receive the signal **110** transmitted from the transmitter device **100**. In the diagram of FIG. **8**B, in contrast to FIG. **8**A, it is assumed that the transmitter device **100** inserted two pilot symbol blocks per second data symbol matrix.

The receiver device **200** of FIG. **8**B may perform a similar operation for the channel estimation as the receiver device **200** of FIG. **8**A. Therefore, a detailed description of the operations performed by each module of the receiver devices **200** is omitted, for the sake of simplicity. The only difference of FIG. **8**B to FIG. **8**A is that symbols received on the known positions of the two blocks of the channel estimation pilot symbols added by the transmitter device **100**, and optionally the interference-free guard symbols surrounding these symbols, are obtained by the receiver device **200**.

Again, a subset of the guard symbols that are corrupted by interference either from data symbols destined to the same user or from data or from pilot symbols destined to other users, may be discarded, and thus, may not be used for channel estimation (as opposed to the subset of guard symbols not corrupted by such interferences but instead only containing a contribution from the pilot symbols of the same user).

In some embodiments, the transmitter device **100** and/or the receiver device **200** may outperform devices using OFDM and single-carrier transmission in terms of diversity on high-mobility links. For example, as in the OTFS, it transforms the time-varying multipath channel into two-

dimensional channel, in the delay-Doppler domain, that may directly represent the geometry of the various reflectors composing the wireless link and the different Doppler frequency shifts they introduce and which, as a result, has much fewer variations across the diagonals of the resulting channel matrix corresponding to each of the delays and the Doppler frequency shifts of these reflectors.

In some embodiments, the transmitter device **100** and/or the receiver device **200** may facilitate tracking time-varying fading, particularly in high-speed vehicle communications. Furthermore, due to the ability to extract the full diversity of channel across time and frequency, a better reliability performance than OFDM may be achieved. Furthermore, the improved performance of the transmitter device **100** and/or the receiver device **200** may be achieved, while the guard or the null symbols overhead is typically lower than in OTFS. Therefore, in some embodiments, the transmitter device **100** and/or the receiver device **200** may allow achieving a higher spectral efficiency value, i.e., higher data throughput, than OTFS (as well as than OFDM and many of its variations).

Moreover, in the intermediate-frequency domain, the channel matrix has a larger part of its power on its main diagonal. This property may be used to perform a first data decoding process in this domain, using simple detection algorithms, e.g., one tap equalization. Furthermore, if the first decoding process fails, the obtained (soft) result of the first decoding process may still be used, e.g., as prior information to initialize any iterative detection algorithm to be applied to the data symbols (thus possibility accelerating its convergence and gaining in both latency and complexity reduction).

In the following, with respect to the description of FIG. **9** to FIG. **14**B and for the sake of simplicity, only additional modules of the transmitter device **100** or the receiver device **200** are described compared to the transmitter device **100** of FIGS. **3**A and **3**B and the receiver device **200** of FIGS. **4**A and **4**B, respectively.

FIG. **9** depicts a schematic view of a block diagram of a transmitter device **100**, which builds on the transmitter device **100** shown in FIGS. **3**A and **3**B. The transmitter device **100** is in particular a LP-LFFT transmitter device **100** with rectangular windowing and CP insertion. The transmitter device **100** of FIG. **9** may comprise a rectangular windowing module and a CP addition module **907**.

The windowing module may perform a rectangular windowing (and hence is not shown in FIG. **9**, since this is equivalent to multiplying symbols with one).

The CP addition module **907** may add a CP to the output of the "row-wise to column-wise" module **305**, as shown in FIG. **9**.

FIGS. **10**A and **10**B depict a schematic view of a block diagram of a receiver device **200**, which builds on the receiver device **200** shown in FIGS. **4**A and **4**B. The receiver device **200** is in particular a LP-LFFT receiver device, and may be used for the case that a rectangular windowing and CP addition is used at the transmitter device **100** (e.g., the LP-LFFT transmitter device of FIG. **9**). For example, the receiver device **200** of FIGS. **10**A and **10**B may comprise a rectangular windowing module and CP removal module **1002**.

The windowing module may perform a rectangular windowing (and hence is not shown, since this is equivalent to multiplying symbols with one).

The CP removal module **1002** may apply a CP removal to the output of module **401**, i.e. may remove a CP from that output, and is arranged before the input of the "column-wise to row-wise" module **404**, as shown in FIGS. **10**A and **10**B.

FIGS. **11**A and **11**B depict a schematic view of a block diagram of a transmitter device **100**, which builds on the transmitter device **100** shown in FIG. **9**. The transmitter device **100** is a LP-LFFT transmitter device with discrete prolate spheroidal sequences (DPSS) windowing and CP insertion. The transmitter device **100** of FIGS. **11**A and **11**B may comprise a DPSS windowing module **1106** and the CP addition module **907** as described for the transmitter device **100** of FIG. **9**.

The DPSS windowing module **1106** of the transmitter device **100** may reduce inter-carrier energy leakage under imperfect time or frequency synchronization. Further, the DPSS windowing module **1106** of the transmitter device **100** may also assist in reducing the out-of-band (**00**B) emissions level. For example, the DPSS windowing module **1106** may perform a multiplication with a DPSS window. The CP addition module **907** may be realized as described for FIG. **9** to add a CP, here to the output of the DPSS windowing module **1106**, as shown in FIGS. **11**A and **11**B.

FIGS. **12**A and **12**B depict a schematic view of a block diagram of a receiver device **200**, which builds on the receiver device **200** shown in FIGS. **10**A and **10**B. The receiver device **200** is a LP-LFFT receiver device, and may be used for the case that a DPSS windowing is used at the transmitter device **100** (e.g., as in the transmitter device **100** shown in FIGS. **11**A and **11**B). The receiver device **200** may comprise a CP removal module **1002**.

The CP removal module **1002** of the receiver device **200** may perform a CP removal before the input of the column-wise to row-wise module **404**, as shown in FIGS. **12**A and **12**B.

The DPSS windowing may allow a reduction of the number of suffix or prefix guard symbols in the intermediate-frequency domain, and hence, it may allow increasing the spectral efficiency.

FIGS. **13**A and **13**B depict a schematic view of a block diagram of a transmitter device **100**, which builds on the transmitter device **100** shown in FIGS. **3**A and **3**B. The transmitter device **100** is a LP-LFFT transmitter device **100** configured to perform a chirp-coefficients windowing and chirp-periodic prefix insertion. The transmitter device **100** may accordingly comprise a chirp windowing module **1306** and a chirp-periodic prefix addition module **1307**.

The chirp windowing module **1306** may perform a quadratic-phase windowing procedure by multiplying the signal in the time domain with a set of window coefficients (e.g., a chirp window sequence) computed based on a delay-Doppler profile of a wireless communication channel of the wireless communication system **1**. The chirp-periodic prefix addition module **1307** may further add a chirp-periodic prefix at a beginning of the signal resulting from the quadratic-phase windowing procedure in the time domain.

Moreover, the chirp windowing module **1306** may be performed by multiplying the symbols at its input with the NM—long chirp sequence $e^{-l2\pi\alpha t^2}$ with t=0, . . . , NM−1, and α being a real number that is referred to as the "chirp parameter" or the "chirp rate". As for the "chirp-periodic" module, it may be realized by first generating an L-long CP from the input (and not the output) of the preceding windowing module, and then by multiplying the symbols of this cyclic prefix with the coefficients $e^{-l2\pi\alpha L^2}$, . . . , $ee^{-l2\pi\alpha 1^2}$ in that order.

FIGS. **14**A and **14**B depict a schematic view of a block diagram of a receiver device **200**, which builds on the receiver device **200** shown in FIGS. **4**A and **4**B. The receiver device **200** is a LP-LFFT receiver device, which may be used in the case of chirp-coefficients windowing at the

transmitter device **100** (e.g., the transmitter device **100** shown in FIGS. **13**A and **13**B). The receiver device **200** may comprise a chirp windowing module **1403** and a chirp-periodic prefix removal module **1402**. The chirp windowing module **1403** and the chirp-periodic prefix removal module **1402** may work like the chirp windowing module **1306** and a chirp-periodic prefix addition module **1307** of the transmitter device **100**, but remove the chirp-periodic prefix.

The chirp windowing module **1403** may represent a multiplication with the NM—long chirp sequence $e^{-i2\pi\alpha t^2}$ with t=0, . . . , NM−1.

Moreover, in some embodiments, the chirp parameter a may be chosen as a function of the delay-Doppler profile of the channel. Moreover, an advantage in terms of guard overhead and equalize complexity reduction may be achieved.

FIG. **15** depicts a schematic view of a flowchart of a method **1500** for a transmitter device **100** for a wireless communication system **1**, according to an embodiment of the disclosure. The method **1500** may be carried out by the transmitter device **100**, as it is described above with respect to the various figures.

The method **1500** comprises a step S**1501** of obtaining a plurality of first data symbol matrices **111**, **112**, **113** in a delay-Doppler domain for a plurality of users by arranging, for each user u of the plurality of users, data symbols of the user u in a first data symbol matrix having a form of $M_u \times N$, M_u being a number of rows specific to the user u, where $M_u > 1$, and N being a number of columns, where N **1**.

The method **1500** further comprises a step S**1502** of obtaining a plurality of second data symbol matrices **121**, **122**, **123** in an intermediate-frequency domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point FFT operation on the first data symbol matrix **111**, **112**, **113** of the user u, the obtained second data symbol matrix **121**, **122**, **123** of the user u having the form of $M_u \times N$, symbols.

The method **1500** further comprises a step S**1503** of obtaining an aggregated matrix **130** in the intermediate-frequency domain for the plurality of users by concatenating the N columns of each of the plurality of second data symbol matrices **121**, **122**, **123** in the intermediate-frequency domain, the aggregated matrix having a form of M×N, M being a number of rows, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of second data symbol matrices for the plurality of users.

FIG. **16** depicts a schematic view of a flowchart of a method **1600** for a receiver device **200**, according to an embodiment of the disclosure. The method **1600** may be carried out by the receiver device **200**, as it is described above.

The method **1600** comprises a step S**1601** of obtaining an aggregated matrix **230** in an intermediate-frequency domain for a plurality of users based on a signal **110** received in a time domain from a transmitter device **100**, the aggregated matrix **230** in the intermediate-frequency domain having a form of M×N, M being a number of rows, where M>1, and N being a number of columns, where N≥1.

The method **1600** further comprises a step S**1602** of obtaining a plurality of first data symbol matrices **221**, **222**, **223** in the intermediate-frequency domain for the plurality of users by deconcatenating the N columns of the aggregated matrix **230** in the intermediate-frequency domain, each first data symbol matrix **221**, **222**, **223** having a form of $M_u \times N$, M u being a number of rows specific to a user u of the plurality of users, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of first data symbol matrices **221**, **222**, **223** for the plurality of users.

The method **1600** further comprises a step S**1603** of obtaining a plurality of second data symbol matrices **211**, **212**, **213** in a delay-Doppler domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point IFFT operation on the first data symbol matrix **221**, **222**, **223** of the user u, the obtained second data symbol matrix **211**, **212**, **213** of the user u having the form of $M_u \times N$.

The present disclosure has been described in conjunction with various embodiments as examples as well as implementations. However, other variations can be understood and effected by those persons skilled in the art and practicing the claimed disclosure, from the studies of the drawings, this disclosure and the independent claims. In the claims as well as in the description the word "comprising" does not exclude other elements or steps and the indefinite article "a" or "an" does not exclude a plurality. A single element or other unit may fulfill the functions of several entities or items recited in the claims. The mere fact that certain measures are recited in the mutual different dependent claims does not indicate that a combination of these measures cannot be used in an advantageous implementation.

What is claimed is:

1. A transmitter device for a wireless communication system, the transmitter device comprising:

processing circuitry configured to:

obtain a plurality of first data symbol matrices in a delay-Doppler domain for a plurality of users by arranging, for each user u of the plurality of users, data symbols of the user u in a first data symbol matrix having a form of $M_u \times N$, M_u being a number of rows specific to the user u, where $M_u > 1$, and N being a number of columns, where N≥1;

obtain a plurality of second data symbol matrices in an intermediate-frequency domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point Fast Fourier Transform (FFT) operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of $M_u \times N$; and

obtain an aggregated matrix in the intermediate-frequency domain for the plurality of users by concatenating the N columns of each of the plurality of second data symbol matrices in the intermediate-frequency domain, the aggregated matrix having a form of M×N, M being a number of rows, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of second data symbol matrices for the plurality of users; and

a transmitter configured to transmit, to a receiver device, a signal from which the aggregated matrix can be obtained.

2. The transmitter device according to claim **1**, wherein the processing circuitry is further configured to insert guard symbols into the aggregated matrix in the intermediate-frequency domain, wherein the guard symbols are inserted between the concatenated N columns of each of the plurality of second data symbol matrices.

3. The transmitter device according to claim **1**, wherein the processing circuitry is further configured to:

insert channel estimation pilot symbols into one or more columns of the first data symbol matrix in the delay-Doppler domain at first positions known to a receiver device, before obtaining the plurality of second data symbol matrices; or

insert channel estimation pilot symbols into one or more columns of the second data symbol matrix in the intermediate frequency-domain at second positions known to the receiver device, before obtaining the aggregated matrix in the intermediate-frequency domain.

4. The transmitter device according to claim **3**, wherein the processing circuitry is further configured to receive a feedback message from the receiver device, the feedback message being indicative of channel state information (CSI) estimated by the receiver device based on the channel estimation pilot symbols inserted in the delay-Doppler domain or based on the channel estimation pilot symbols inserted in the intermediate-frequency domain.

5. The transmitter device according to claim **1**, wherein the processing circuitry is further configured to obtain a phase-weighted aggregated matrix in the intermediate-frequency domain by performing a per-column phase-weighting operation on the aggregated matrix in the intermediate-frequency domain, wherein the per-column phase-weighting operation comprises multiplying each column of the aggregated matrix in the intermediate-frequency domain with a phase factor weighting matrix.

6. The transmitter device according to claim **5**, wherein the processing circuitry is further configured to perform a M-point Inverse FFT (IFFT) operation on the obtained phase-weighted aggregated matrix in the intermediate-frequency domain to convert the phase-weighted aggregated matrix in the intermediate-frequency domain to a phase-weighted aggregated matrix in the delay-Doppler domain.

7. The transmitter device according to claim **6**, wherein the processing circuitry is further configured to:

obtain a signal in the delay-Doppler domain based on the phase-weighted aggregated matrix in the delay-Doppler domain; and

perform an N-point IFFT operation on the signal in the delay-Doppler domain to convert the signal in the delay-Doppler domain to a signal in a time domain, wherein the signal in the time domain includes a number of N×M symbols.

8. The transmitter device according to claim **7**, wherein the processing circuitry is further configured to:

perform a quadratic-phase windowing procedure by multiplying the signal in the time domain with a set of window coefficients computed based on a delay-Doppler profile of a wireless communication channel of the wireless communication system; and

add a chirp-periodic prefix at a beginning of the signal resulting from the quadratic-phase windowing procedure in the time domain.

9. A receiver device for a wireless communication system, the receiver device comprising:

processing circuitry configured to:

obtain an aggregated matrix in an intermediate-frequency domain for a plurality of users based on a signal received in a time domain from a transmitter device, the aggregated matrix in the intermediate-frequency domain having a form of M×N, M being a number of rows, where M>1, and N being a number of columns, where N≥1;

obtain a plurality of first data symbol matrices in the intermediate-frequency domain for the plurality of users by deconcatenating the N columns of the aggregated matrix in the intermediate-frequency domain, each first data symbol matrix having a form of M_u×N, M_u being a number of rows specific to a user u of the plurality of users, wherein M is greater than a sum of the respective numbers of rows Mu of the plurality of first data symbol matrices for the plurality of users; and

obtain a plurality of second data symbol matrices in a delay-Doppler domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point Inverse Fast Fourier Transform (IFFT) operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of M_u×N.

10. The receiver device according to claim **9**, wherein the processing circuitry is further configured to obtain a second signal in the time domain by:

discarding from the signal received in the time domain at least one prefix inserted at the transmitter device; and

multiplying the signal received in the time domain with a set of window coefficients computed based on a delay-Doppler profile of a wireless communication channel of the wireless communication system.

11. The receiver device according to claim **10**, wherein the processing circuitry is further configured to obtain a signal in the delay-Doppler domain by performing an N-point FFT operation on the second signal in the time domain.

12. The receiver device according to claim **11**, wherein the processing circuitry is further configured to:

obtain a phase-weighted aggregated matrix in the delay-Doppler domain based on the signal in the delay-Doppler domain; and

perform an M-point FFT operation on the phase-weighted aggregated matrix in the delay-Doppler domain to convert the phase weighted aggregated matrix in the delay-Doppler domain to a phase-weighted aggregated matrix in the intermediate-frequency domain.

13. The receiver device according to claim **12**, wherein the processing circuitry is further configured to obtain the aggregated matrix in the intermediate-frequency domain by performing a per-column phase-weighting operation on the phase-weighted aggregated matrix in the intermediate-frequency domain, wherein the per-column phase-weighting operation comprises multiplying each column of the phase-weighted aggregated matrix in the intermediated frequency domain with a diagonal phase-weighting matrix.

14. The receiver device according to claim **13**, wherein the processing circuitry is further configured to:

extract guard symbols from the N columns of the aggregated matrix in the intermediate-frequency domain; and

obtain the plurality of first data symbol matrices in the intermediate-frequency domain by deconcatenating the N columns of the aggregated matrix in the intermediate-frequency domain.

15. The receiver device according to claim **9**, wherein the aggregated matrix in the intermediate-frequency domain further includes channel estimation pilot symbols inserted at the transmitter device in one or more columns.

16. The receiver device according to claim **15**, wherein the processing circuitry is further configured to estimate channel state information (CSI) based on the channel estimation pilot symbols in the delay-Doppler domain or in the intermediate-frequency domain.

17. The receiver device according to claim **16**, wherein the processing circuitry is further configured to send a feedback message to the transmitter device, the feedback message being indicative of the estimated CSI.

18. A method for a transmitter device, the method comprising:

obtaining a plurality of first data symbol matrices in a delay-Doppler domain for a plurality of users by

arranging, for each user u of the plurality of users, data symbols of the user u in a first data symbol matrix having a form of $M_u \times N$, M_u being a number of rows specific to the user u, where $M_u > 1$, and N being a number of columns, where $N \geq 1$;

obtaining a plurality of second data symbol matrices in an intermediate-frequency domain for the plurality of users by performing, for each user u of the plurality of users, a M_u-point Fast Fourier Transform (FFT) operation on the first data symbol matrix of the user u, the obtained second data symbol matrix of the user u having the form of $M_u \times N$; and

obtaining an aggregated matrix in the intermediate-frequency domain for the plurality of users by concatenating the N columns of each of the plurality of second data symbol matrices in the intermediate-frequency domain, the aggregated matrix having a form of $M \times N$, M being a number of rows, wherein M is greater than a sum of the respective numbers of rows M_u of the plurality of second data symbol matrices for the plurality of users; and

transmitting, to a receiver device, a signal from which the aggregated matrix can be obtained.

19. A non-transitory computer readable medium having stored thereon processor executable instructions that, when executed by a processor, cause the processor to carry out the method of claim **18**.

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