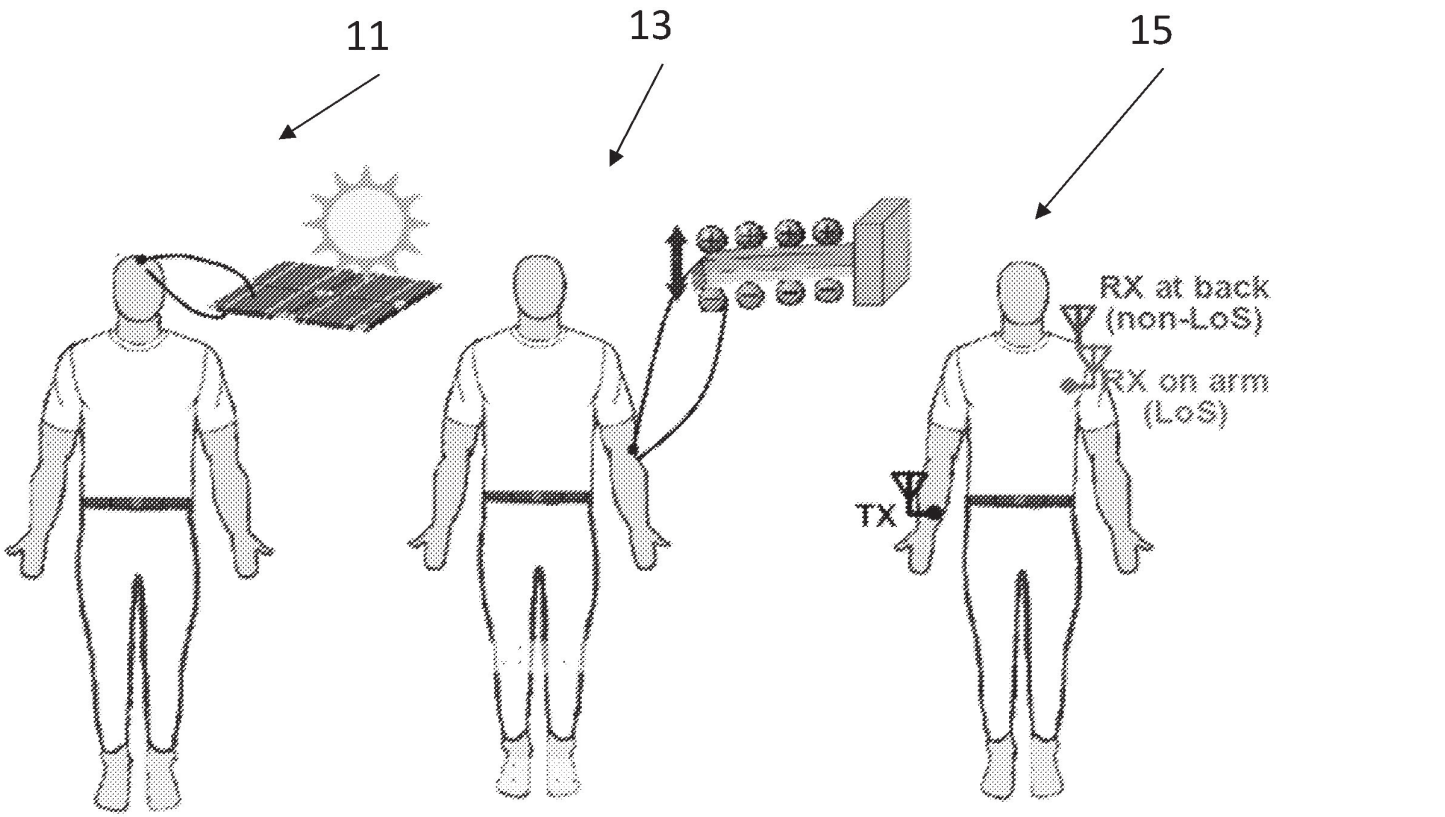

11
13
15
RX at back
(non-LoS)
RX on arm
(LoS)
TX
Photovoltaics
Coverage:
light exposure
Piezo/Triboelectrics
Coverage:
electrostatics
RF Power transfer
Coverage:
Line of Sight (LoS)

Fig. 1

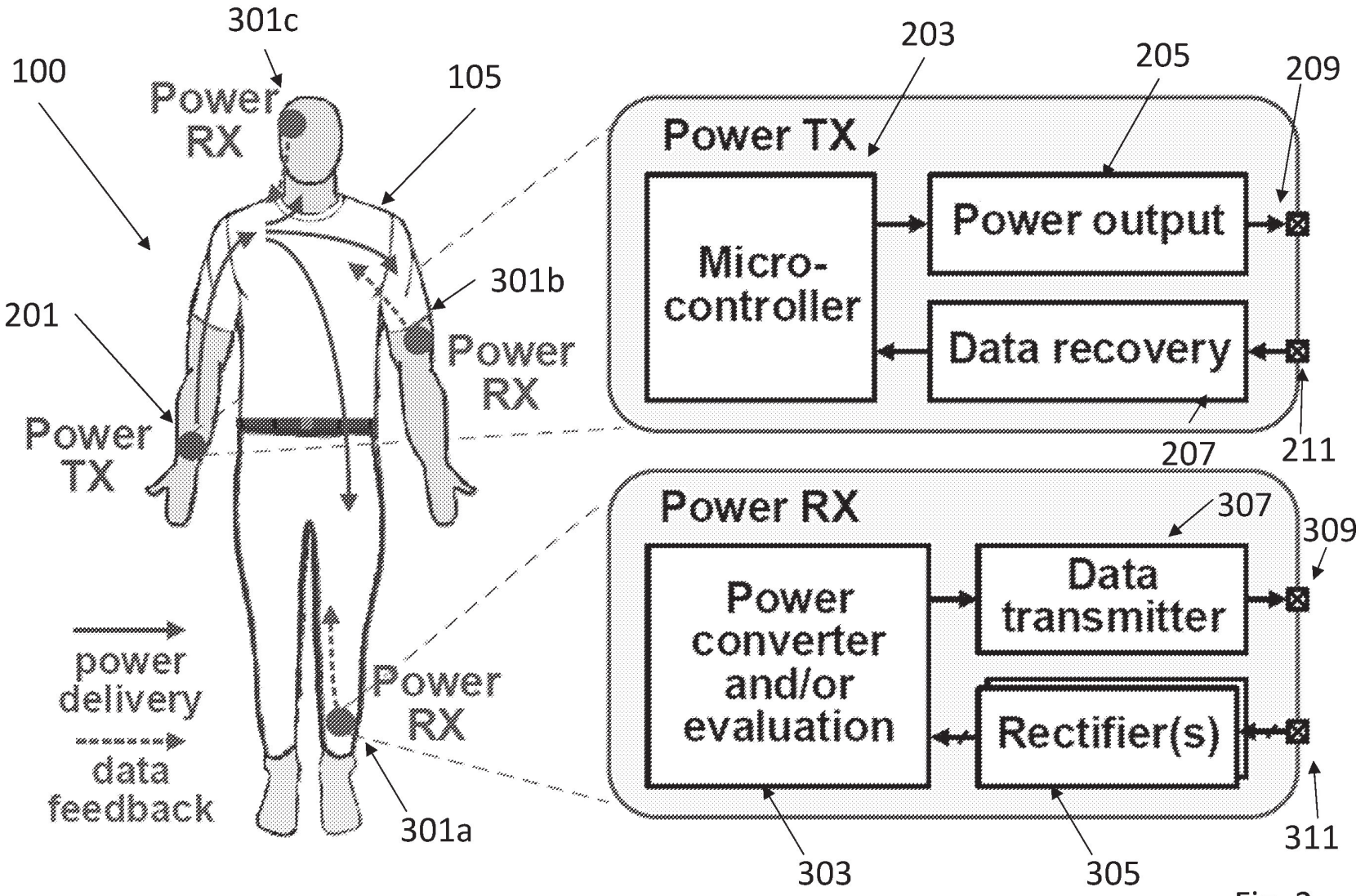

100
301c
Power RX
105
201
301b
Power RX
Power TX
Power RX
power delivery
data feedback
301a
203
205
209
Power TX
Micro-controller
Power output
Data recovery
207
211
Power RX
307
309
Power converter and/or evaluation
Data transmitter
Rectifier(s)
303
305
311

Fig. 2

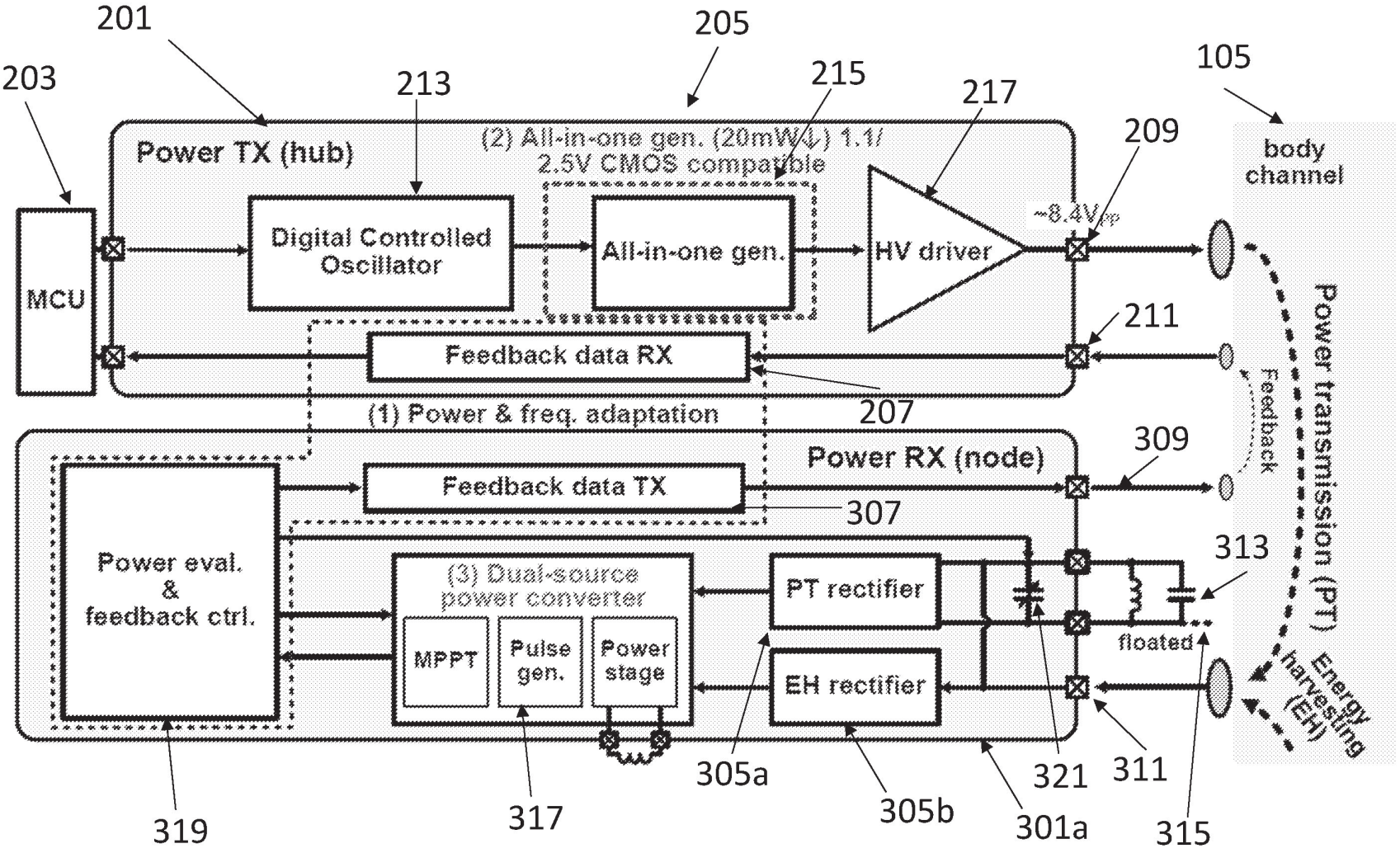

201
205
105
203
213
215
217
209
Power TX (hub)
(2) All-in-one gen. (20mW↓) 1.1/
2.5V CMOS compatible
body
channel
MCU
Digital Controlled
Oscillator
All-in-one gen.
HV driver
~8.4V
Power transmission (PT)
211
Feedback data RX
Feedback
207
(1) Power & freq. adaptation
309
Power RX (node)
Feedback data TX
307
313
Power eval.
&
feedback ctrl.
(3) Dual-source
power converter
PT rectifier
floated
MPPT
Pulse
gen.
Power
stage
EH rectifier
Energy
harvesting
(EH)
305a
321
311
305b
301a
315
319
317

Fig. 3

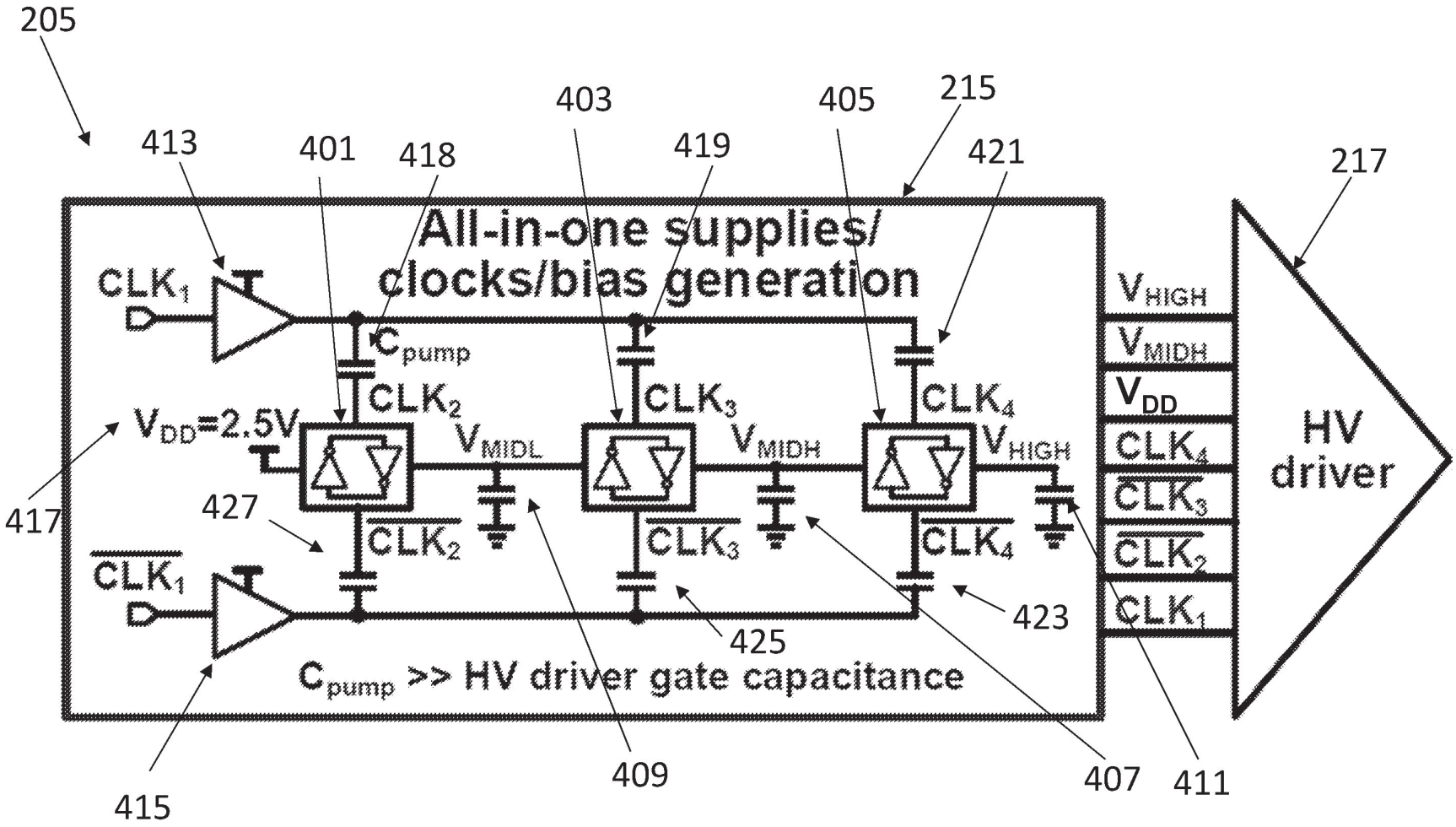

205
413
401
418
403
419
405
215
421
217
All-in-one supplies/
clocks/bias generation
CLK1
Cpump
CLK2
CLK3
CLK4
VDD=2.5V
VMIDL
VMIDH
VHIGH
417
427
CLK2
CLK3
CLK4
CLK1
425
423
Cpump >> HV driver gate capacitance
VHIGH
VMIDH
VDD
CLK4
CLK3
CLK2
CLK1
HV
driver
415
409
407
411

Fig. 4

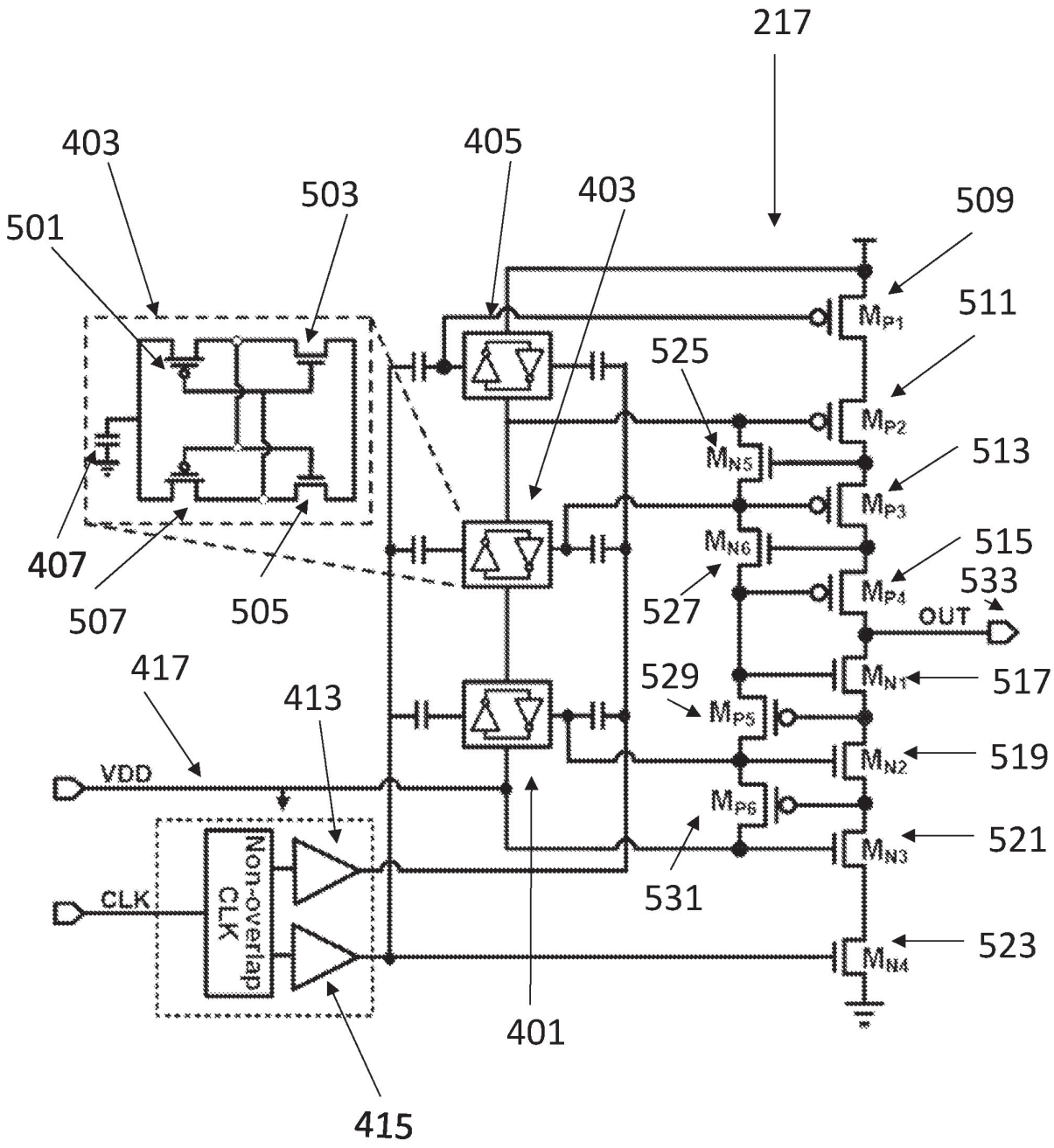

217
403
405
403
503
501
509
511
525
513
515
533
OUT
517
519
521
523
529
527
531
407
507
505
417
413
VDD
CLK
Non-overlap CLK
401
415

Fig. 5

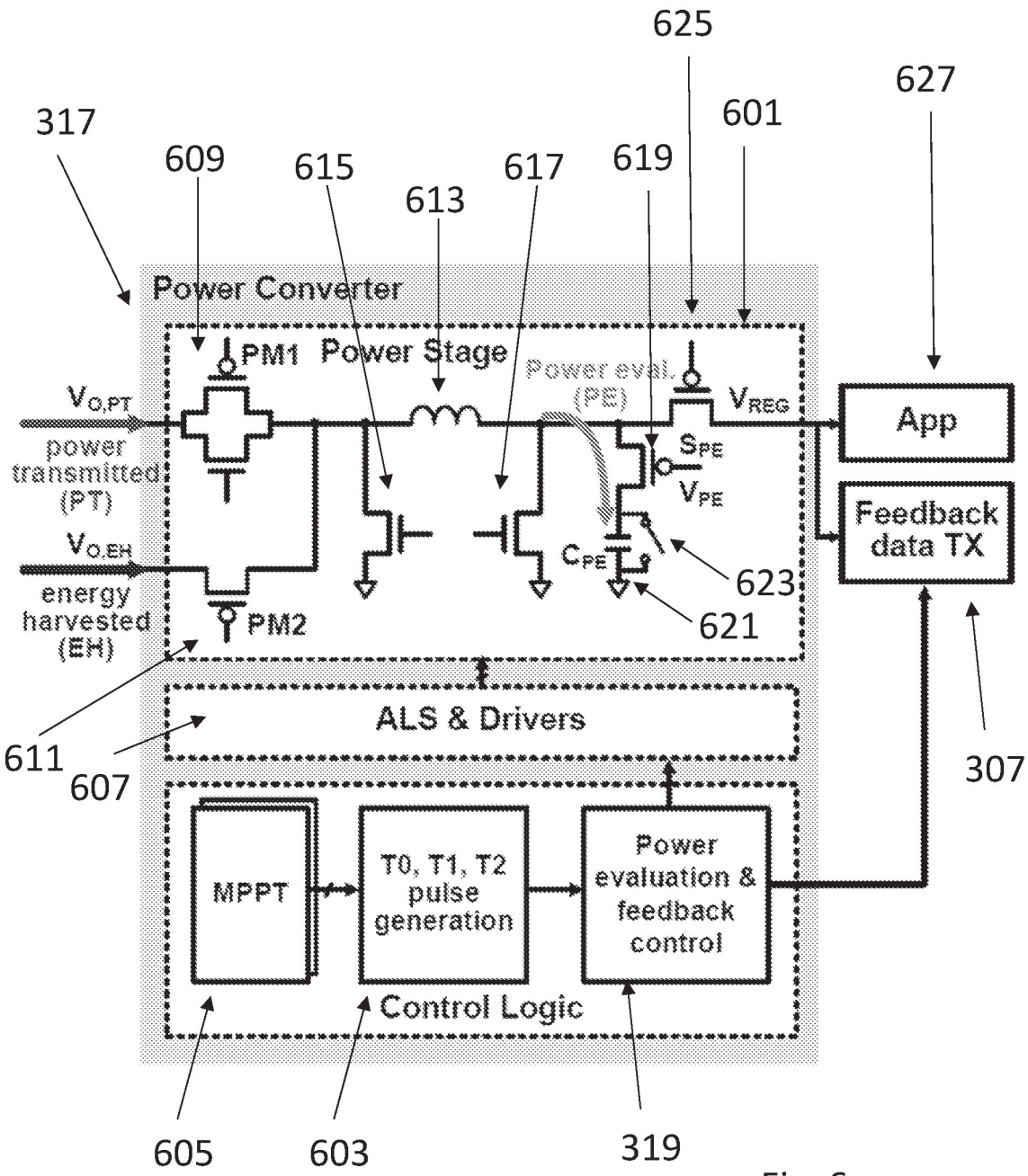

625
627
317
601
609
615
617
619
613
Power Converter
PM1
Power Stage
Power eval. (PE)
V_{REG}
App
$V_{O,PT}$
power transmitted (PT)
S_{PE}
V_{PE}
Feedback data TX
$V_{O,EH}$
energy harvested (EH)
C_{PE}
623
621
PM2
ALS & Drivers
611
607
307
MPPT
T0, T1, T2 pulse generation
Power evaluation & feedback control
Control Logic
605
603
319

Fig. 6

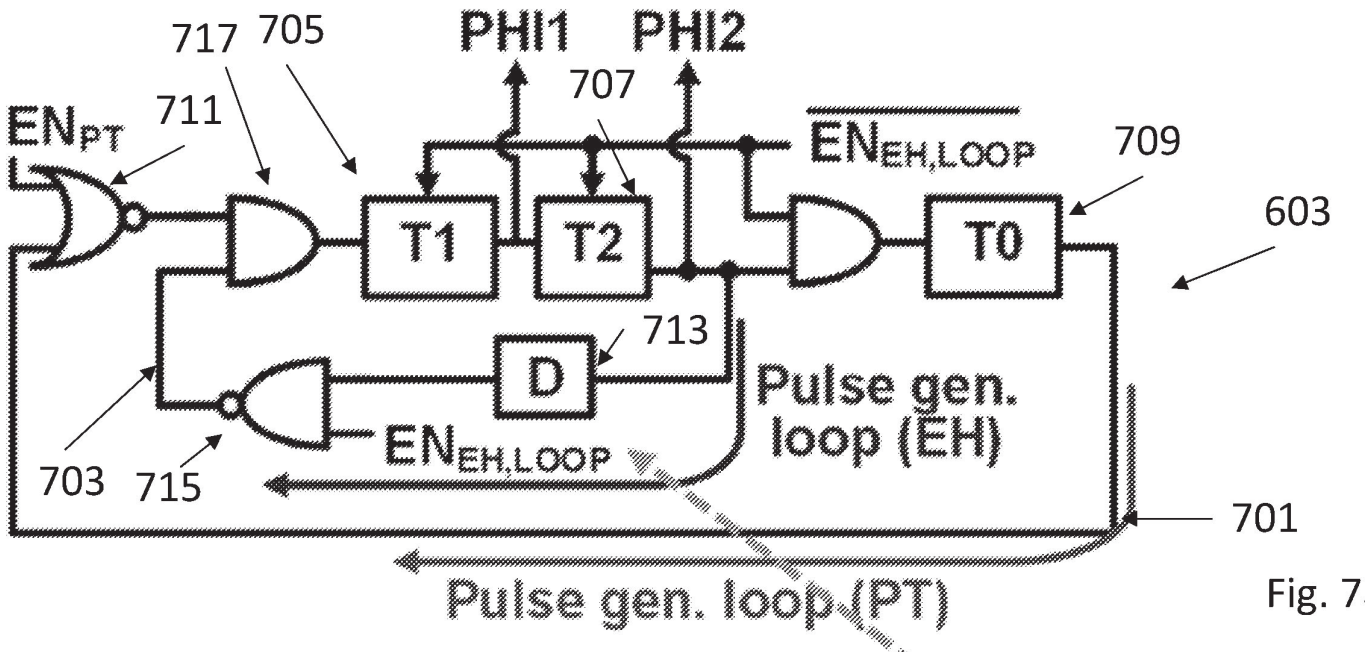

717
705
PHI1
PHI2
707
711
EN_{PT}
$\overline{EN_{EH,LOOP}}$
709
603
T1
T2
T0
713
D
Pulse gen. loop (EH)
$EN_{EH,LOOP}$
703
715
701
Pulse gen. loop (PT)

Fig. 7a

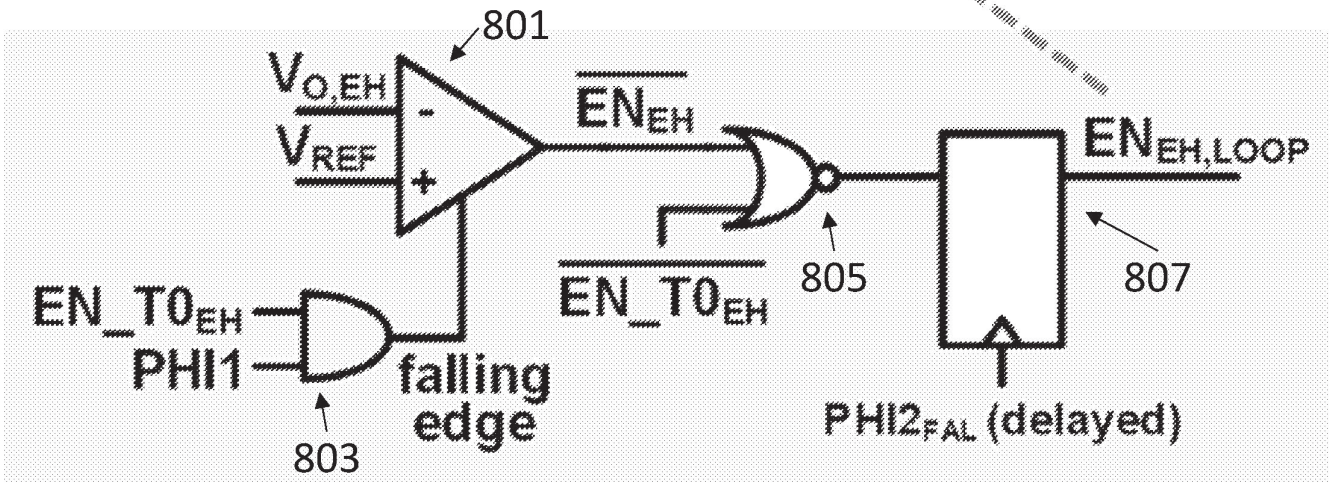

801
$V_{O,EH}$
V_{REF}
-
+
$\overline{EN_{EH}}$
$EN_{EH,LOOP}$
$\overline{EN_T0_{EH}}$
805
807
EN_T0_{EH}
PHI1
falling edge
803
$PHI2_{FAL}$ (delayed)

Fig. 7b

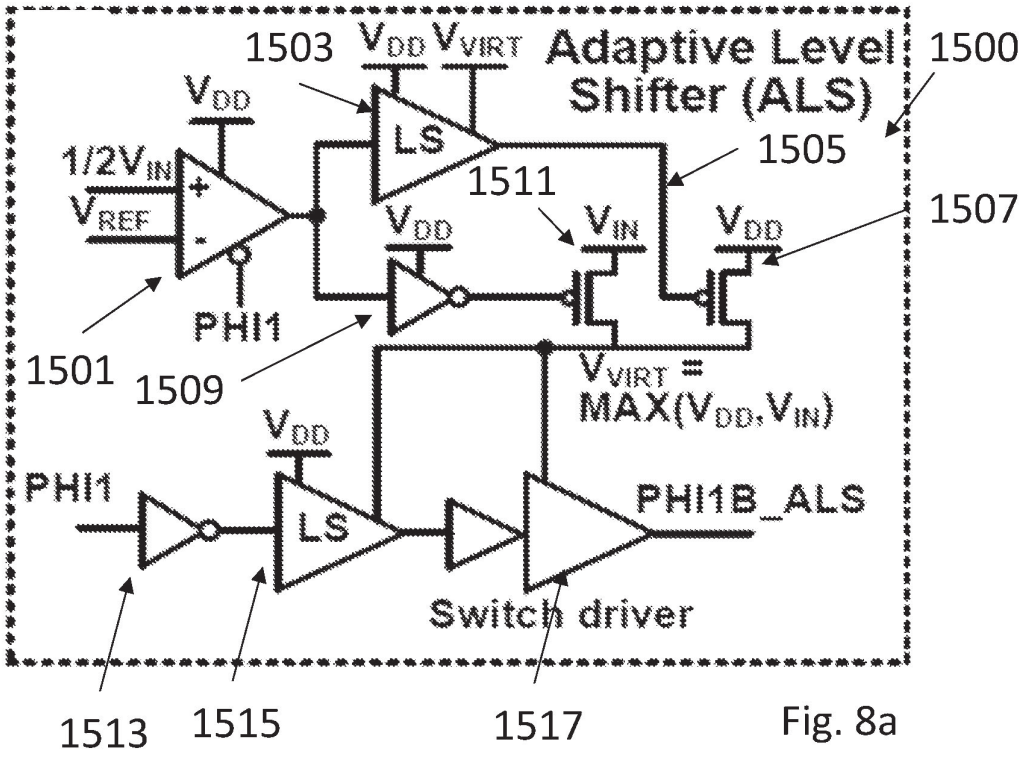

1503
V_{DD} V_{VIRT}
Adaptive Level Shifter (ALS)
1500
V_{DD}
LS
1505
1/2V_{IN}
V_{REF}
1511
1507
V_{DD}
V_{IN}
V_{DD}
PHI1
1501
1509
V_{VIRT} = MAX(V_{DD},V_{IN})
V_{DD}
PHI1
LS
PHI1B_ALS
Switch driver
1513
1515
1517

Fig. 8a

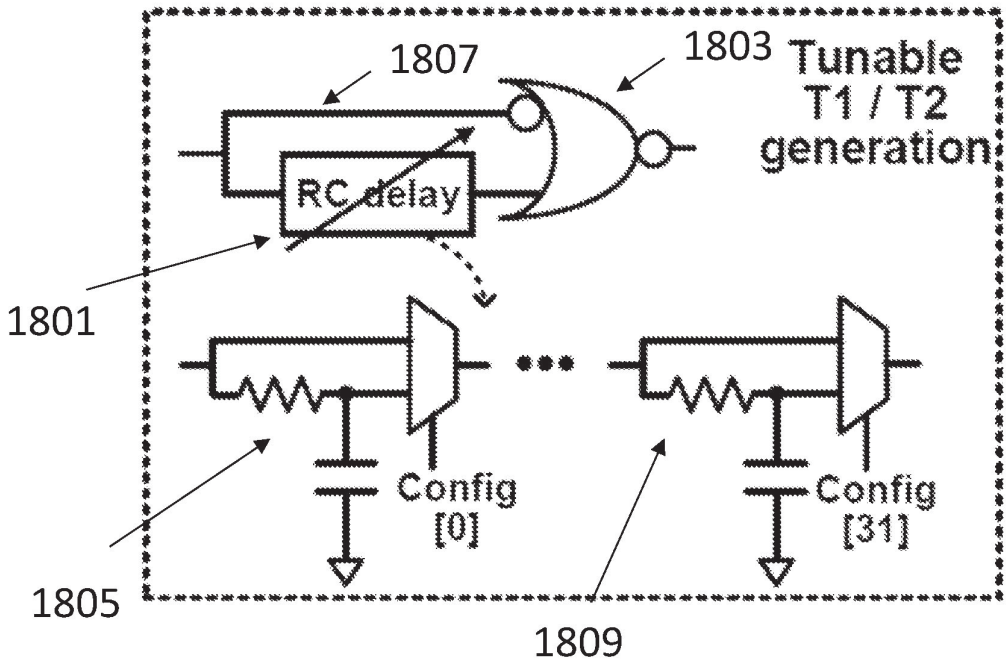

1807
1803
Tunable T1 / T2 generation
RC delay
1801
Config [0]
Config [31]
1805
1809

Fig. 8b

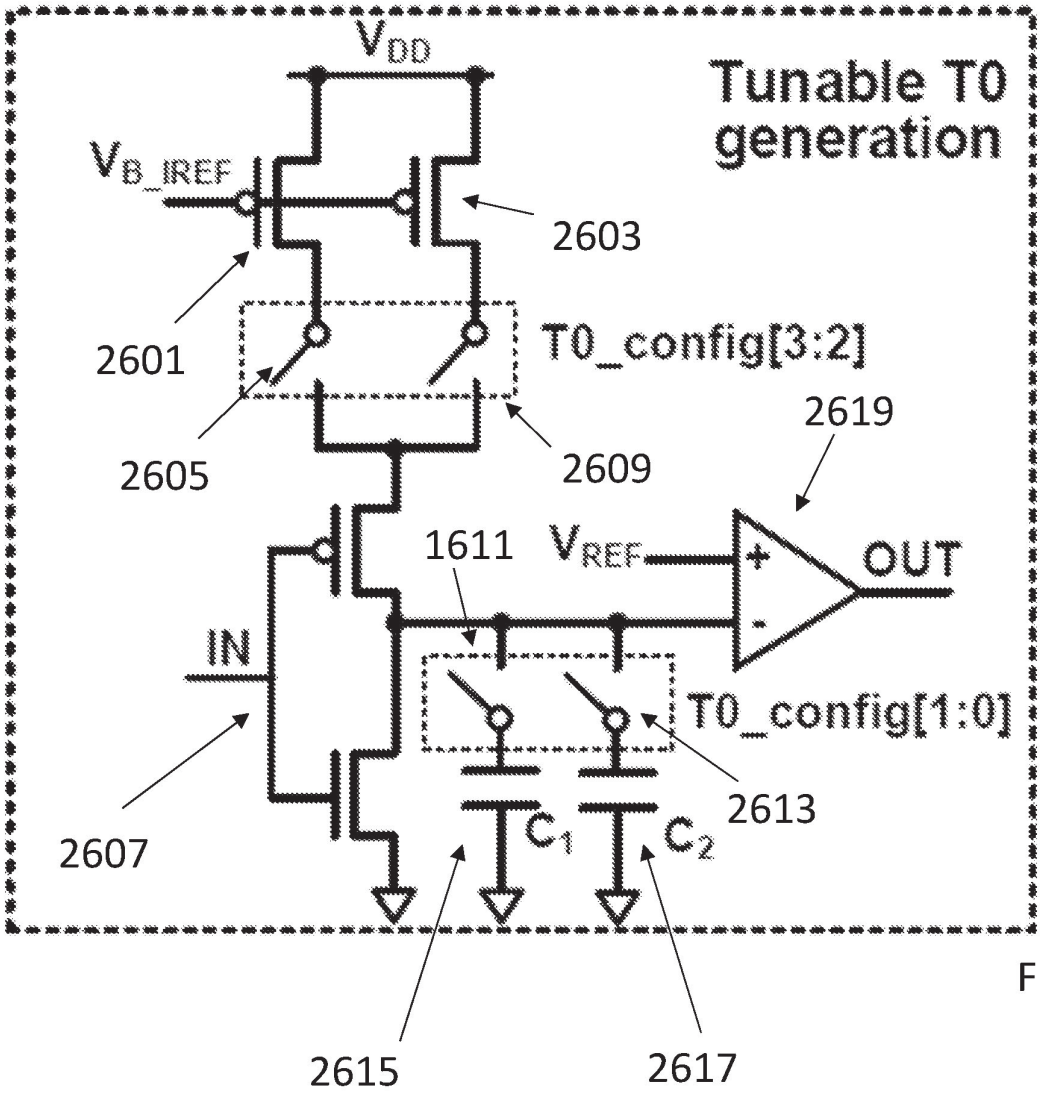

Tunable T0 generation
V_{DD}
V_{B_IREF}
2603
2601
T0_config[3:2]
2605
2609
2619
1611
V_{REF}
+
-
OUT
IN
T0_config[1:0]
2613
2607
C_1
C_2
2615
2617

Fig. 8c

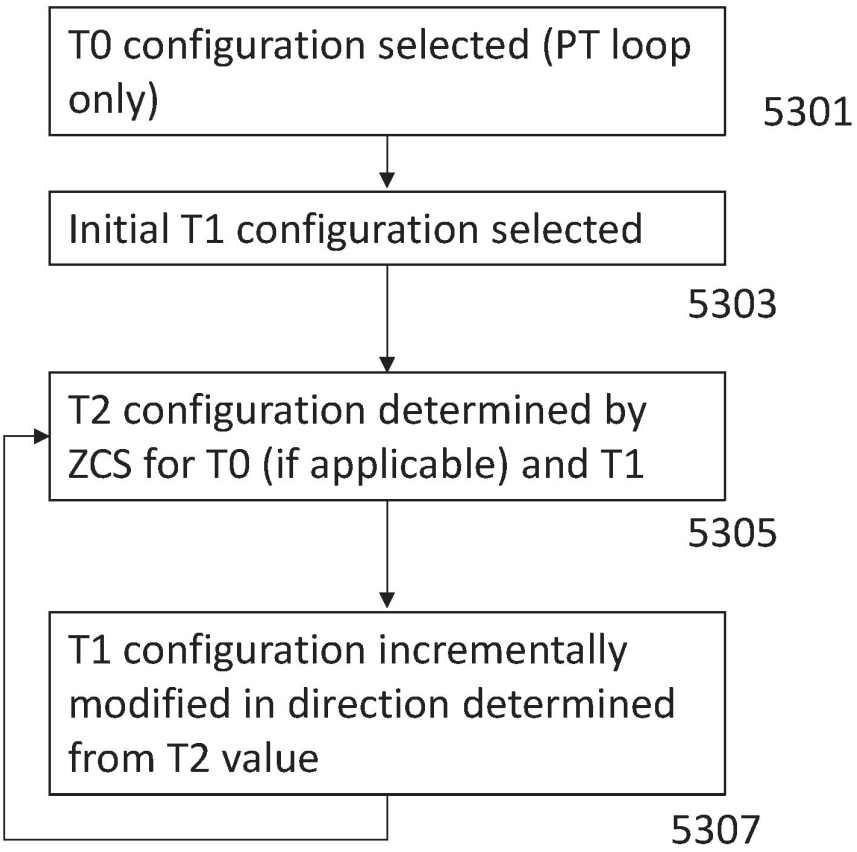

T0 configuration selected (PT loop only)
5301
Initial T1 configuration selected
5303
T2 configuration determined by ZCS for T0 (if applicable) and T1
5305
T1 configuration incrementally modified in direction determined from T2 value
5307

Fig. 8d

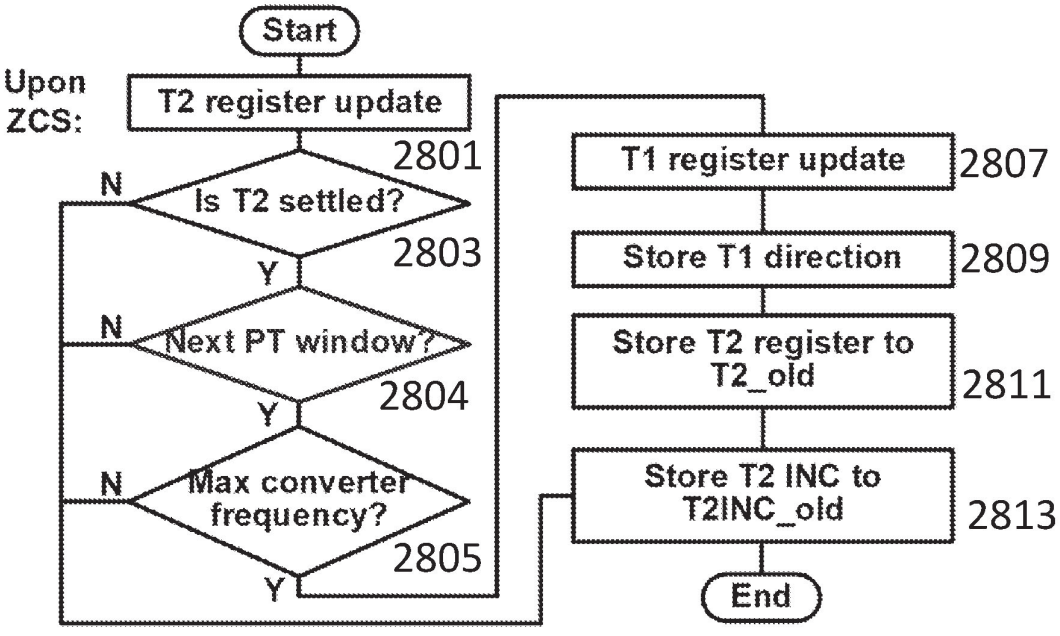

Start
Upon ZCS:
T2 register update
2801
N
Is T2 settled?
2803
Y
N
Next PT window?
2804
Y
N
Max converter frequency?
2805
Y
T1 register update
2807
Store T1 direction
2809
Store T2 register to T2_old
2811
Store T2 INC to T2INC_old
2813
End

Fig. 8e

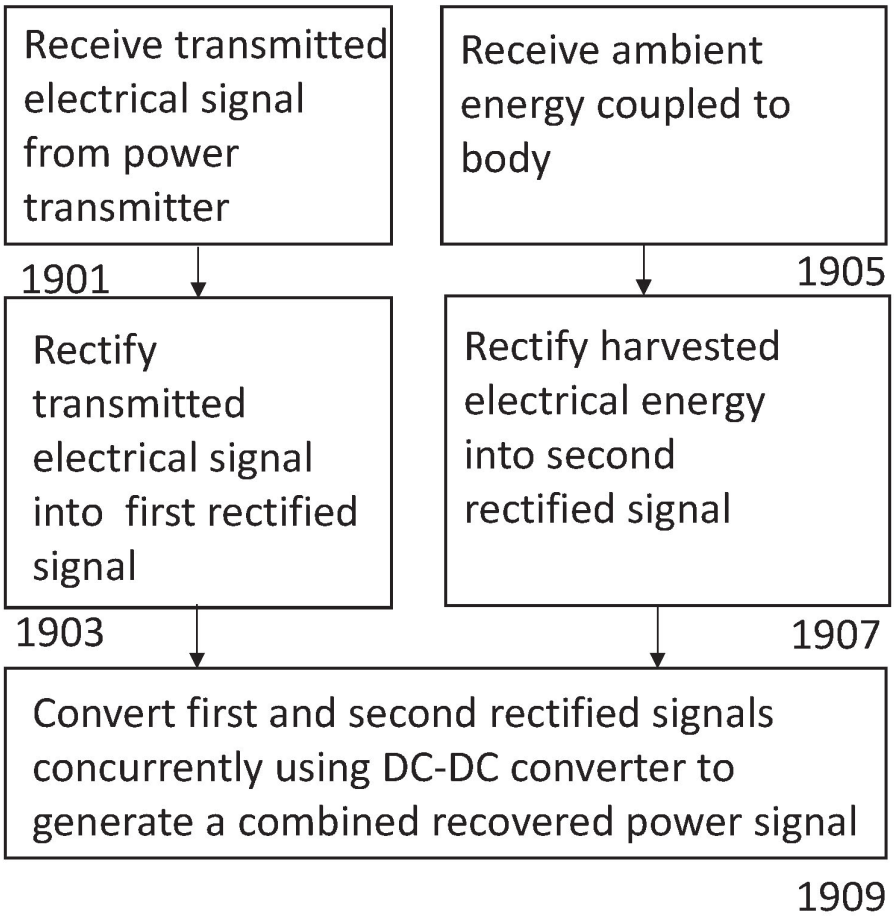

Receive transmitted electrical signal from power transmitter
1901
Rectify transmitted electrical signal into first rectified signal
1903
Receive ambient energy coupled to body
1905
Rectify harvested electrical energy into second rectified signal
1907
Convert first and second rectified signals concurrently using DC-DC converter to generate a combined recovered power signal
1909

Fig. 8f

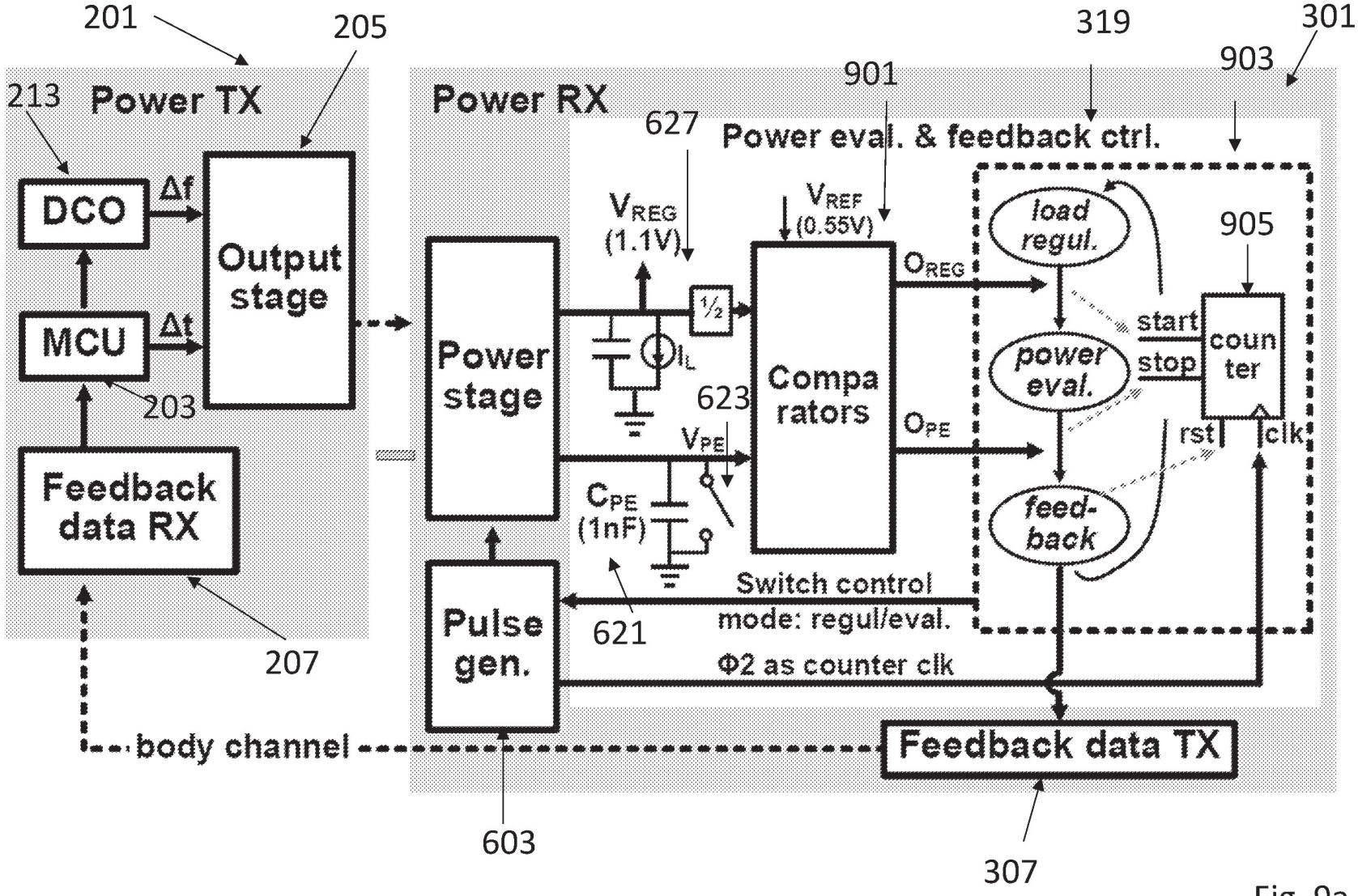

201
205
319
301a
903
901
213
Power TX
Power RX
627
Power eval. & feedback ctrl.
DCO
Δf
Output stage
MCU
Δt
203
Feedback data RX
207
Power stage
Pulse gen.
VREG (1.1V)
VREF (0.55V)
½
IL
623
VPE
CPE (1nF)
621
Compa rators
OREG
OPE
load regul.
power eval.
feed-back
905
start
stop
coun ter
rst
clk
Switch control
mode: regul/eval.
Φ2 as counter clk
body channel
Feedback data TX
603
307

Fig. 9a

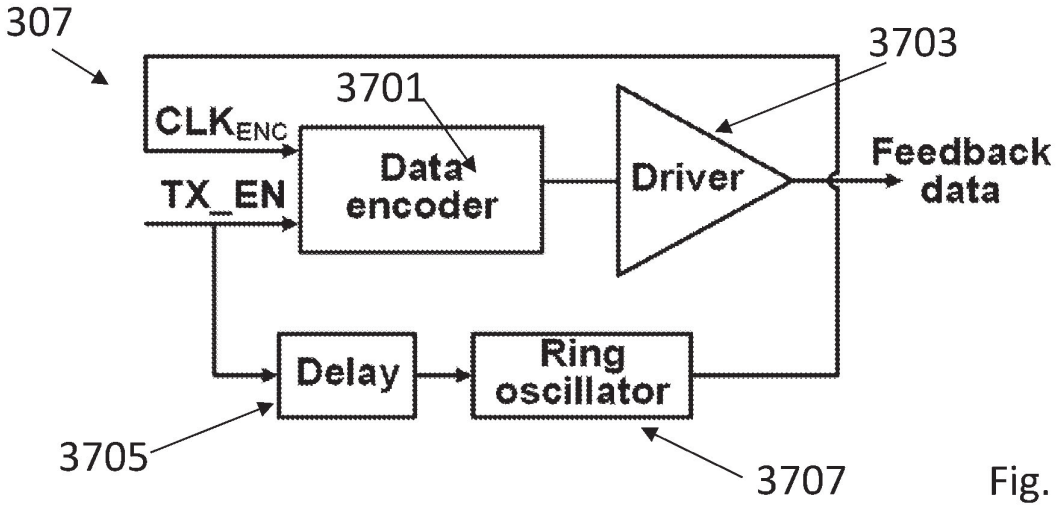

307
3703
3701
CLK_ENC
TX_EN
Data encoder
Driver
Feedback data
Delay
Ring oscillator
3705
3707

Fig. 9b

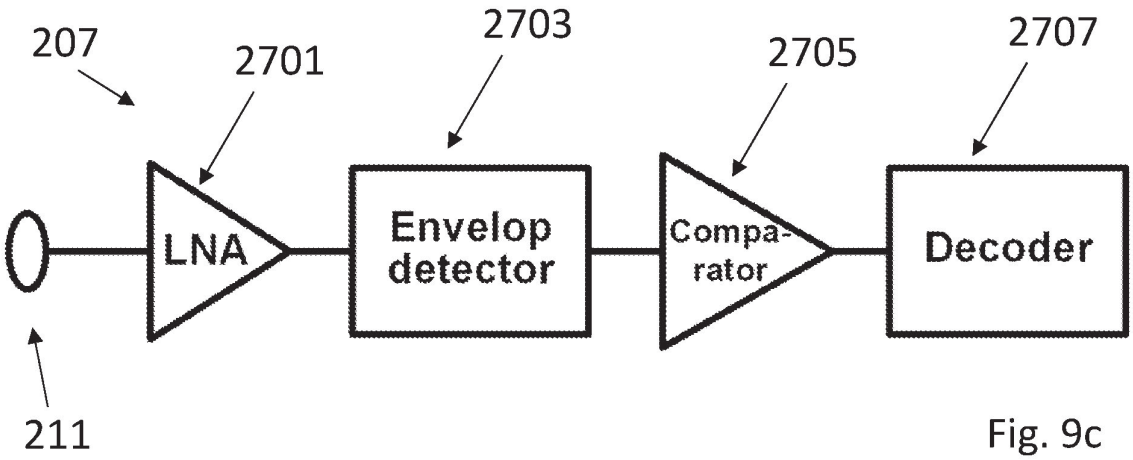

207
2701
2703
2705
2707
LNA
Envelop detector
Compa-rator
Decoder
211

Fig. 9c

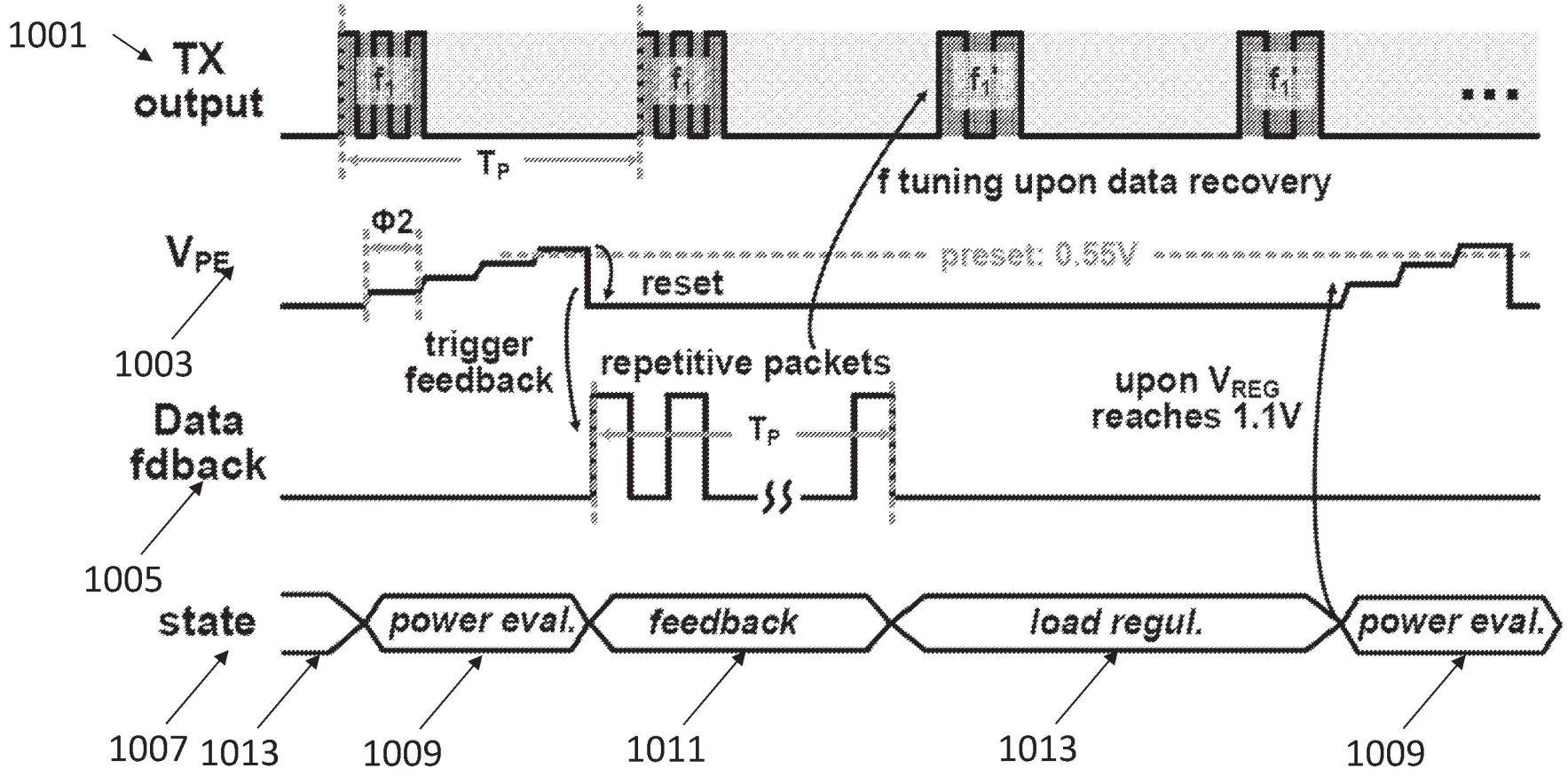

1001
TX output
f_1
f_1
f_1'
f_1'
T_P
f tuning upon data recovery
Φ2
V_{PE}
preset: 0.55V
reset
1003
trigger feedback
repetitive packets
upon V_{REG} reaches 1.1V
Data fdback
T_P
1005
state
power eval.
feedback
load regul.
power eval.
1007
1013
1009
1011
1013
1009

Fig. 10a

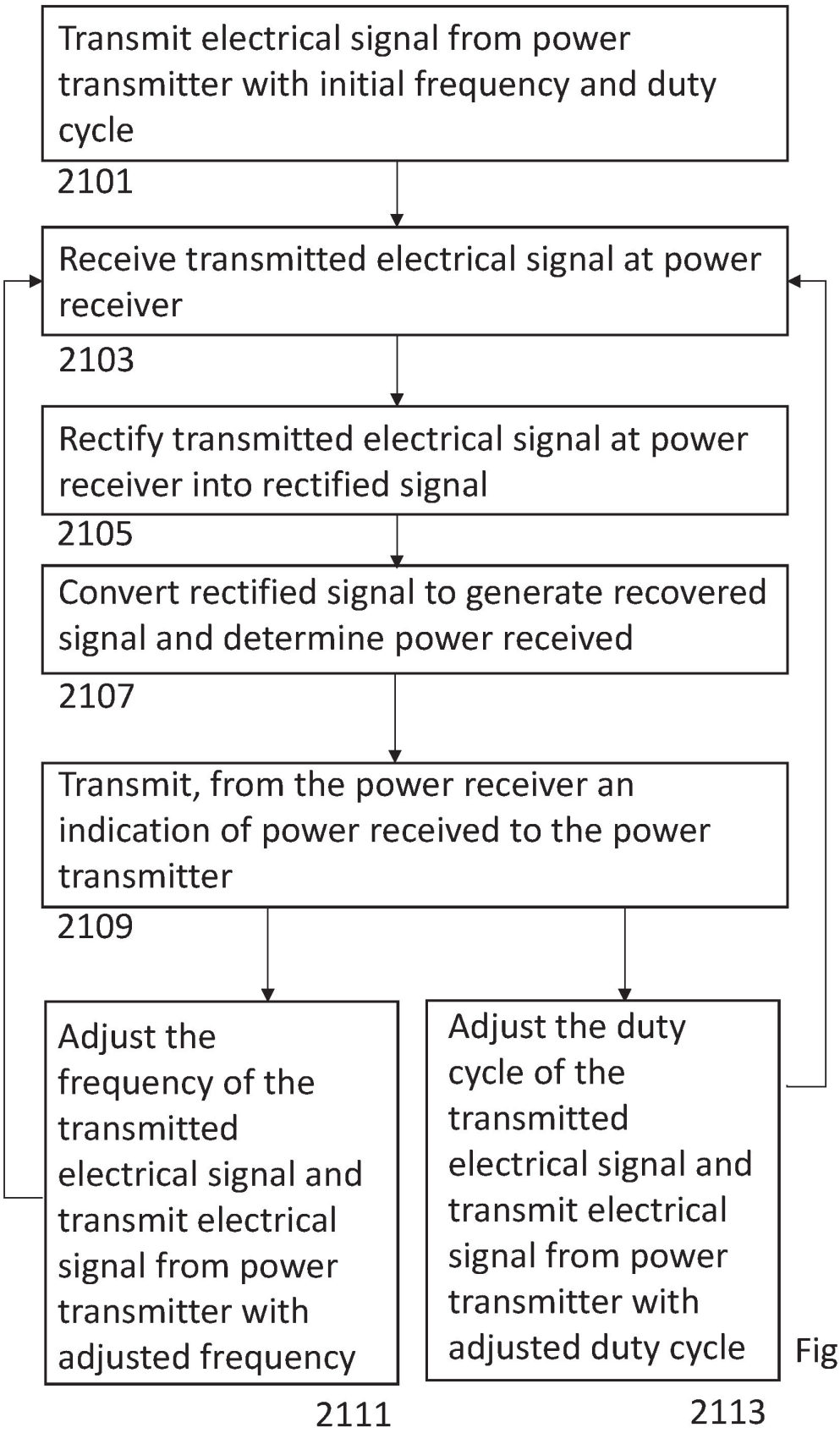

Transmit electrical signal from power transmitter with initial frequency and duty cycle
2101
Receive transmitted electrical signal at power receiver
2103
Rectify transmitted electrical signal at power receiver into rectified signal
2105
Convert rectified signal to generate recovered signal and determine power received
2107
Transmit, from the power receiver an indication of power received to the power transmitter
2109
Adjust the frequency of the transmitted electrical signal and transmit electrical signal from power transmitter with adjusted frequency
2111
Adjust the duty cycle of the transmitted electrical signal and transmit electrical signal from power transmitter with adjusted duty cycle
2113

Fig. 10b

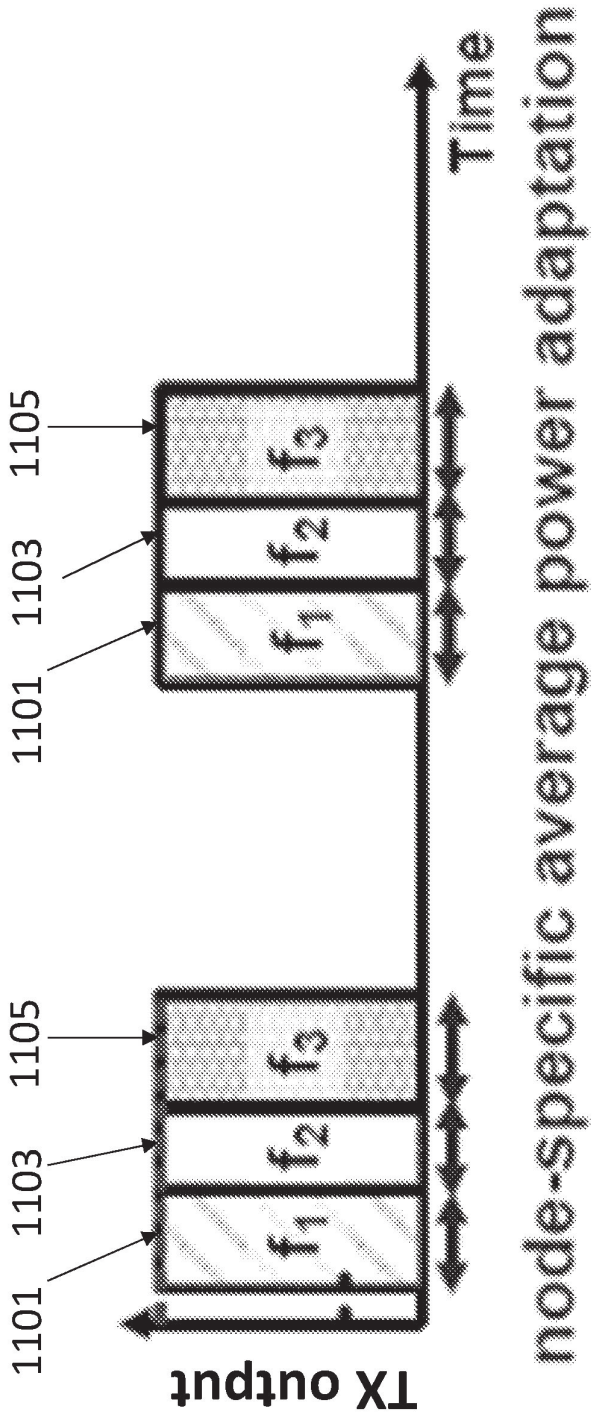

node-specific average power adaptation
TX output
Time
1101
1103
1105
f1
f2
f3
1101
1103
1105
f1
f2
f3

Fig. 11

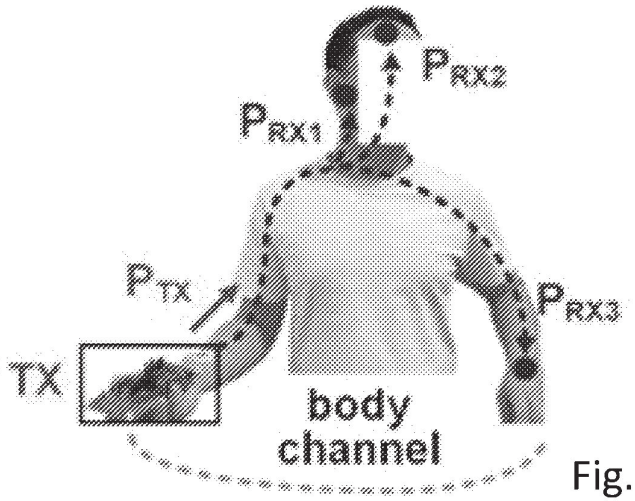


Fig. 12a

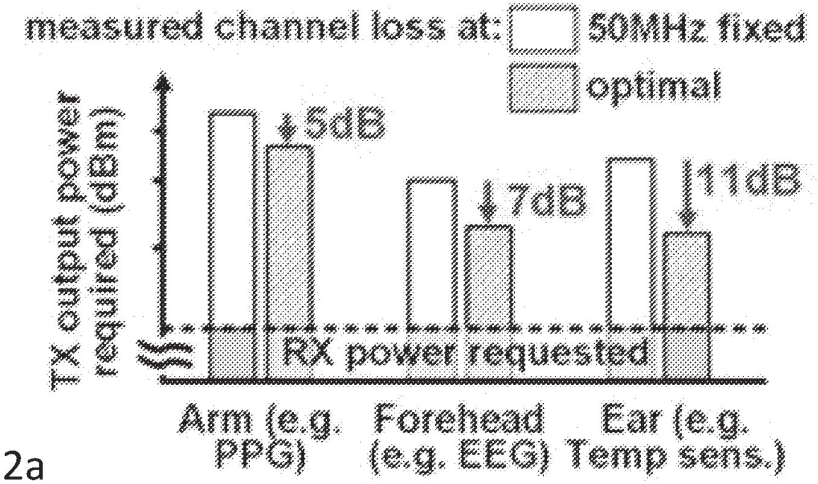


Fig. 12b

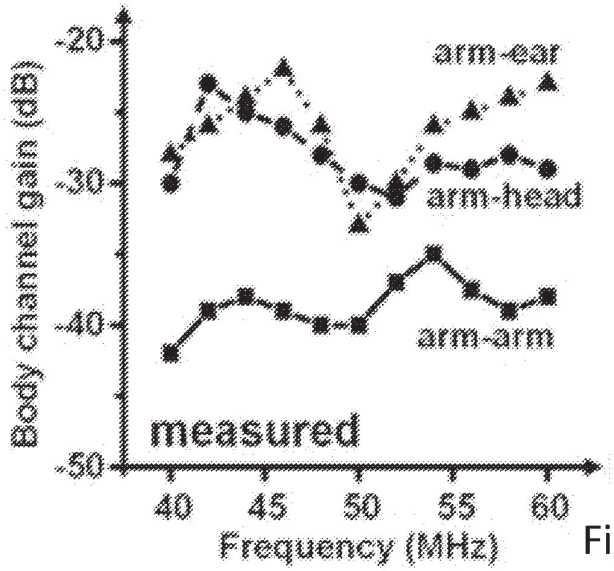


Fig. 12c

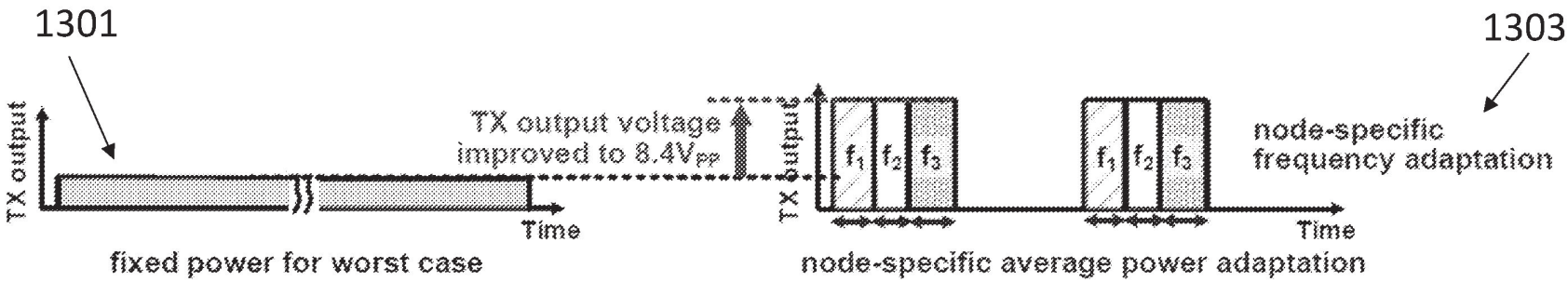

1301
1303
TX output
TX output voltage
improved to 8.4V$_{PP}$
Time
fixed power for worst case
TX output
f_1 f_2 f_3
f_1 f_2 f_3
node-specific
frequency adaptation
Time
node-specific average power adaptation

Fig. 13

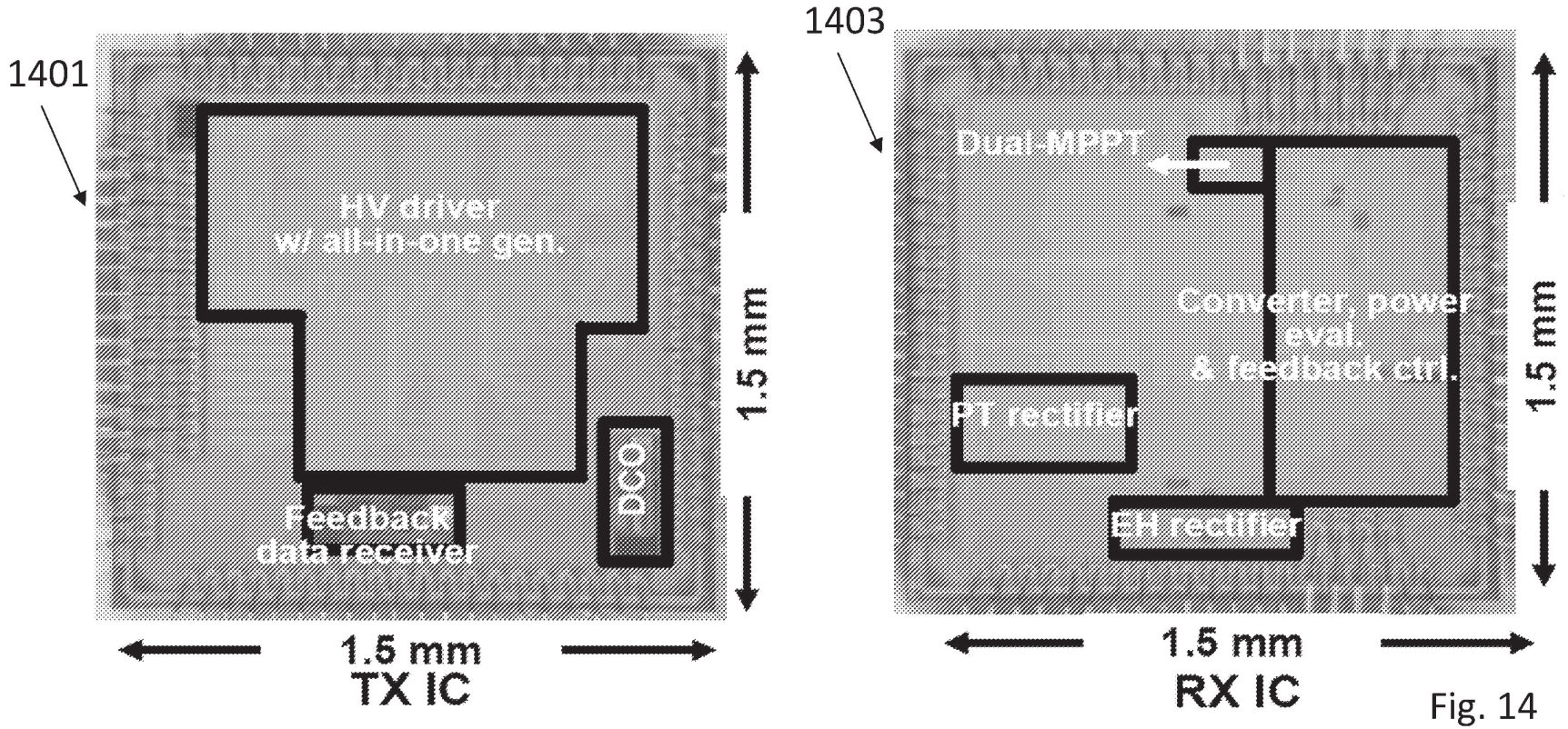

1401
HV driver
w/ all-in-one gen.
Feedback
data receiver
DCO
1.5 mm
1.5 mm
TX IC
1403
Dual-MPPT
Converter, power
eval
& feedback ctrl.
PT rectifier
EH rectifier
1.5 mm
1.5 mm
RX IC

Fig. 14

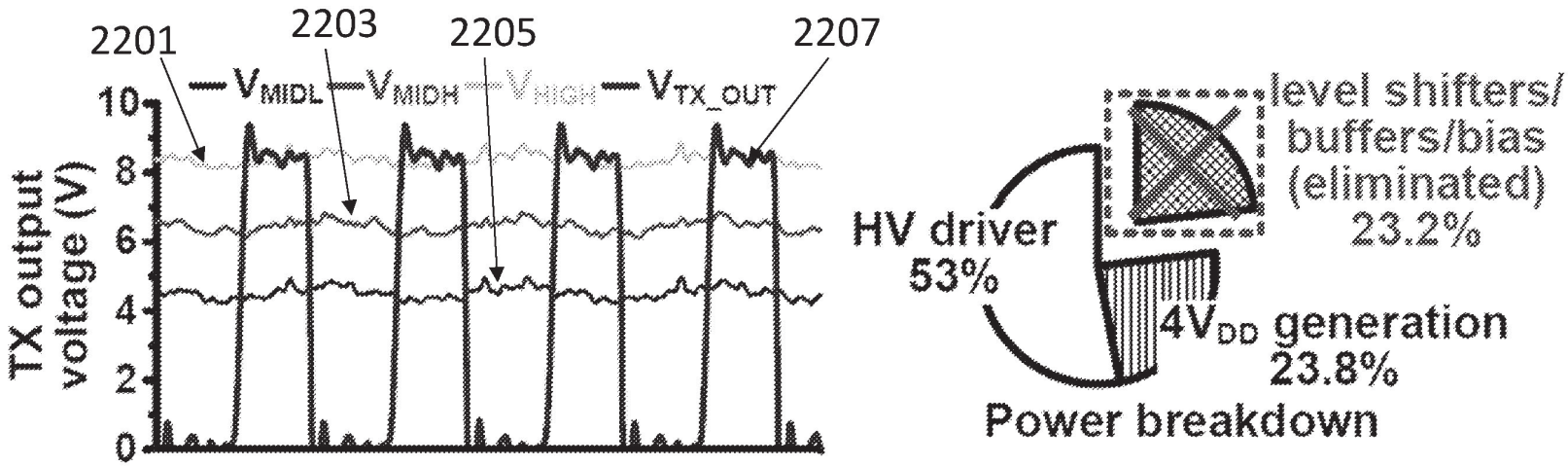

2201
2203
2205
2207
V_{MIDL}
V_{MIDH}
V_{HIGH}
V_{TX_OUT}
TX output voltage (V)
10
8
6
4
2
0
level shifters/ buffers/bias (eliminated) 23.2%
HV driver 53%
$4V_{DD}$ generation 23.8%
Power breakdown

Fig. 15

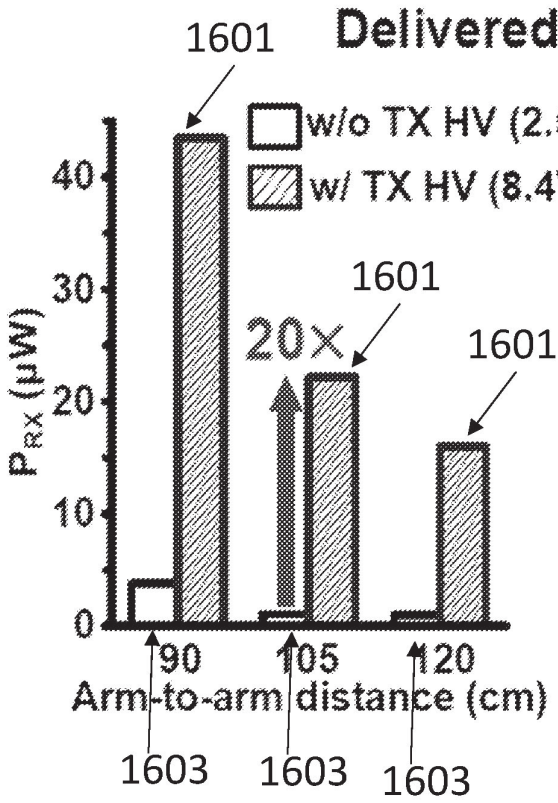


Fig. 16a

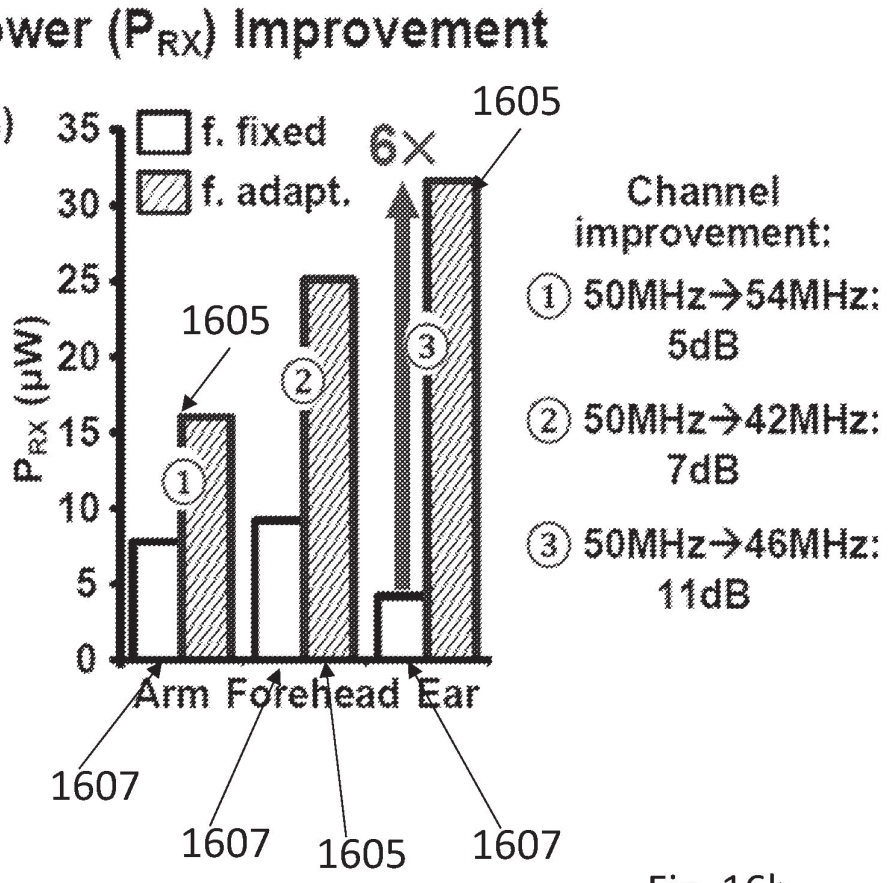


Fig. 16b

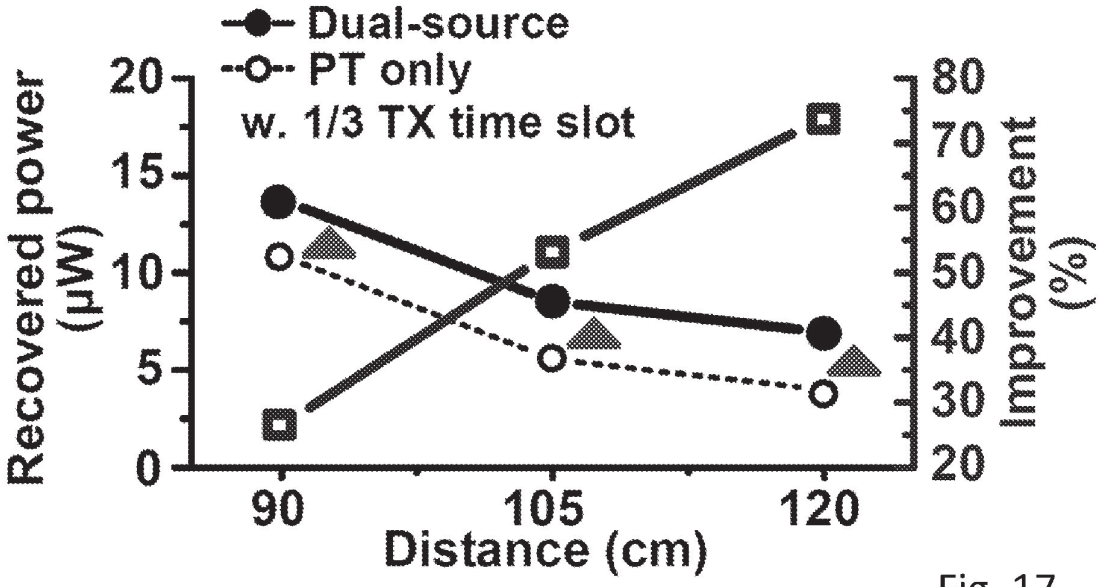

Dual-source
PT only
w. 1/3 TX time slot
Recovered power (μW)
Improvement (%)
Distance (cm)
0
5
10
15
20
20
30
40
50
60
70
80
90
105
120

Fig. 17

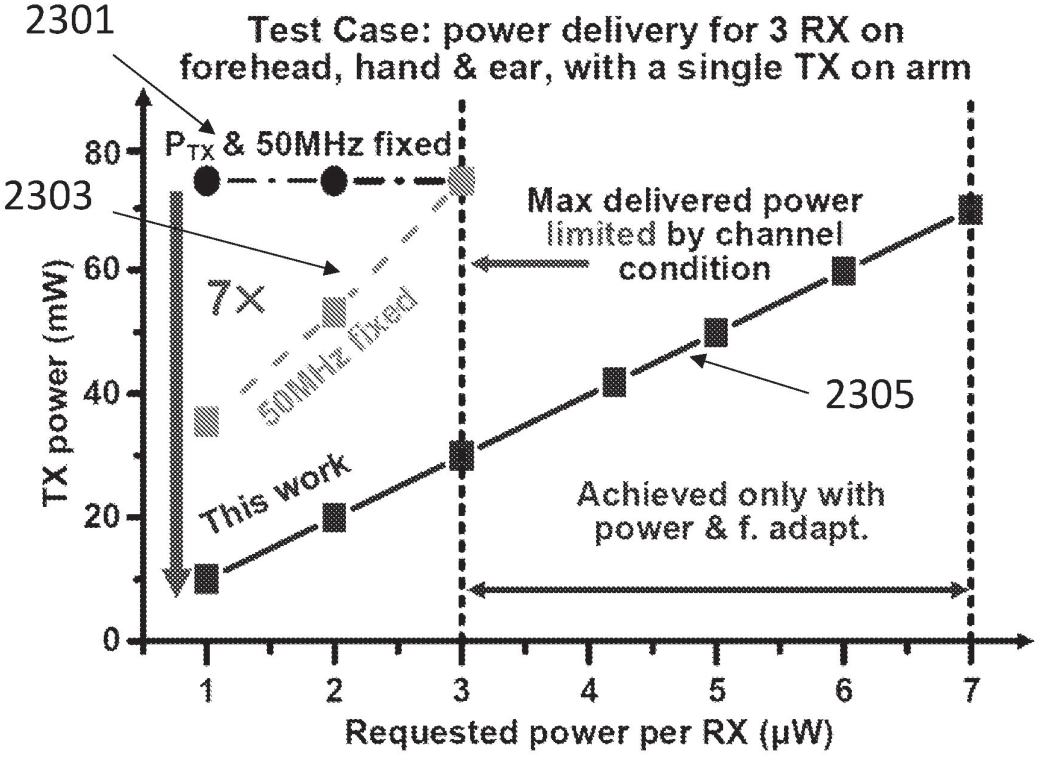

2301
Test Case: power delivery for 3 RX on forehead, hand & ear, with a single TX on arm
P_{TX} & 50MHz fixed
2303
Max delivered power limited by channel condition
7×
50MHz fixed
2305
This work
Achieved only with power & f. adapt.
TX power (mW)
Requested power per RX (μW)
0
20
40
60
80
1
2
3
4
5
6
7

Fig. 18