FOCUSED WIRELESS POWER TRANSFER

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CONTENTS

1. INTRODUCTION

WIRELESS POWER TRANSFER (WPT)

- Inductive Wireless Power Transfer
  - High power, high efficiency
  - Small distance

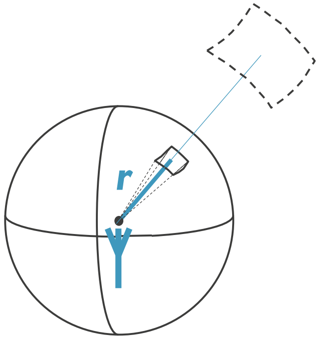
It's not wireless
It's *plugless*

- Radiative Wireless Power Transfer
  - (Ultra) low power, low/medium efficiency
  - Larger distance

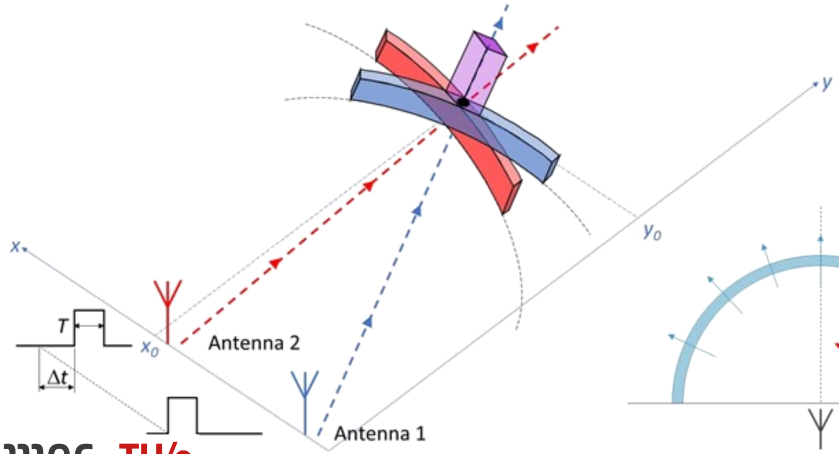
- Large distance, high power?
  - Increase transmit power?
  - Focus

1. INTRODUCTION

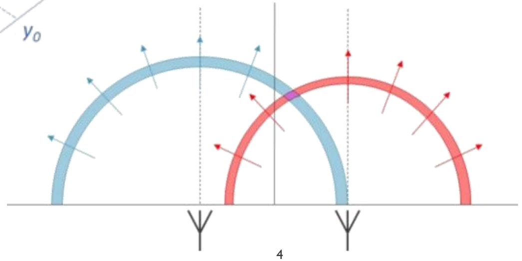
RADIATIVE WIRELESS POWER TRANSFER



- Spherical spreading of electromagnetic fields
  - Power density drops as $1/r^2$
  - Transmit power limited (interference, health)



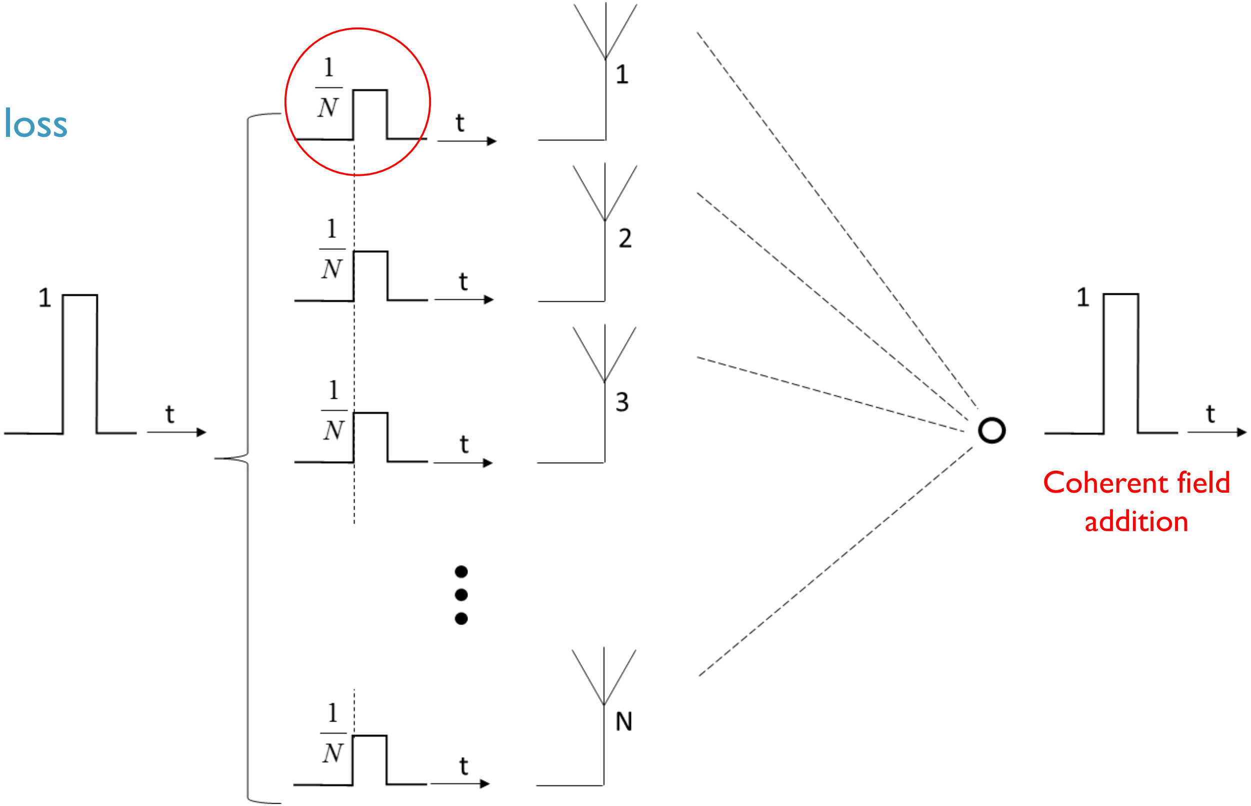
- Pulse-delayed array antenna transmission
  - Creation of focal area in space and time
  - Increased power density



2. POWER GAIN

During the pulse, the array transmits the maximum allowed power

- Pulses, no delays
  - Isotropic radiators
  - No spherical spreading loss

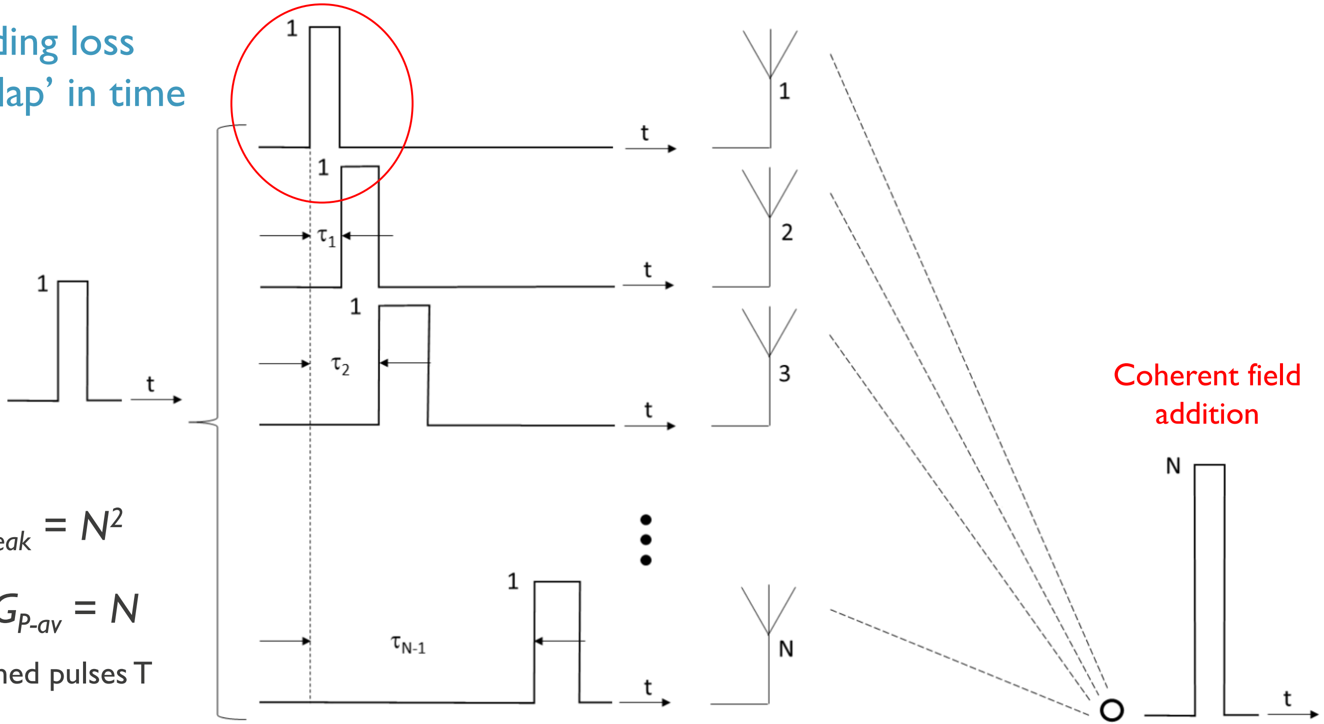


2. POWER GAIN

At every instant in time, the array transmits the maximum allowed power

At every instant in time, only one array element is active

- Pulses, delayed
  - Isotropic radiators
  - No spherical spreading loss
  - Pulsed do not 'overlap' in time



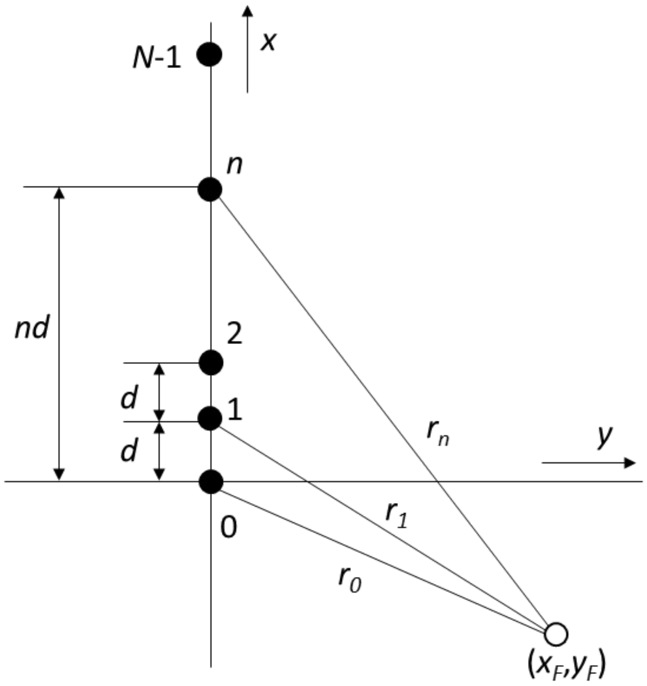
Max. Peak-power Gain: $G_{P\text{-}peak} = N^2$

Max. Average-power Gain: $G_{P\text{-}av} = N$

Pulse width T/N, periodicity combined pulses T

2. POWER GAIN

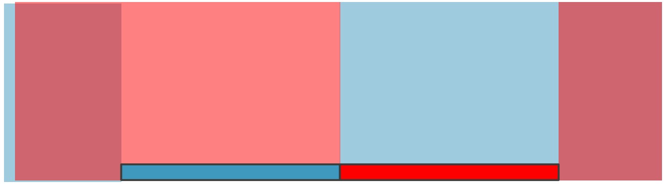
- Path length differences and time delays



$$\Delta t_n = \frac{r_n - r_{n-1}}{c} = \frac{\sqrt{(nd-x_F)^2+y_F^2} - \sqrt{([n-1]d-x_F)^2+y_F^2}}{c}$$

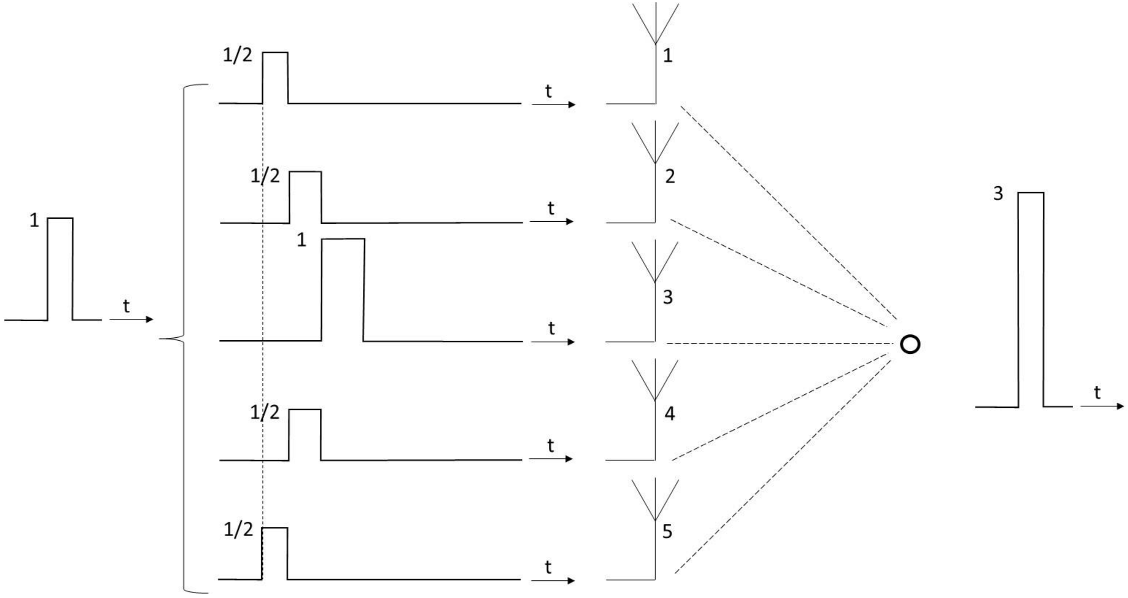
- Focal points can be created in the near- and far-field

$G_{P\text{-}peak} = N^2$ only possible for $x \leq 0$ or $x \geq (N-1)d$



2. POWER GAIN

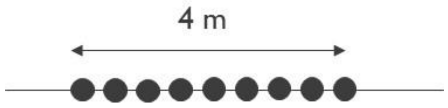
- Worst case example

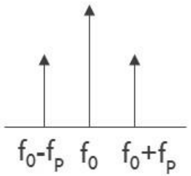


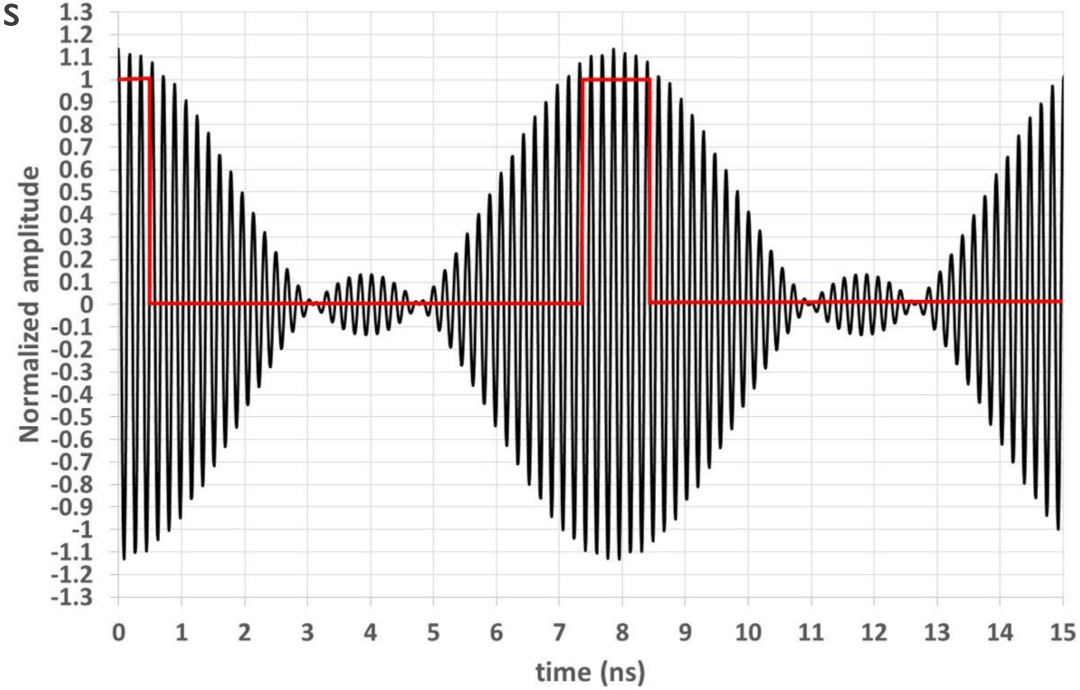
- $N = 5, \; x_F = 0$
- $G_{P\text{-}peak} = ((N-1)*1/2+1)^2$
  $= (N+1)^2/2^2 = 9$

3. EXAMPLE

- Use ISM frequencies and bandwidths
  - f_0 = 5.597 GHz, BW = 154 MHz
  - f_p = 127 MHz, T_p = 7.874 ns
  - N = 9, d = 0.5 m



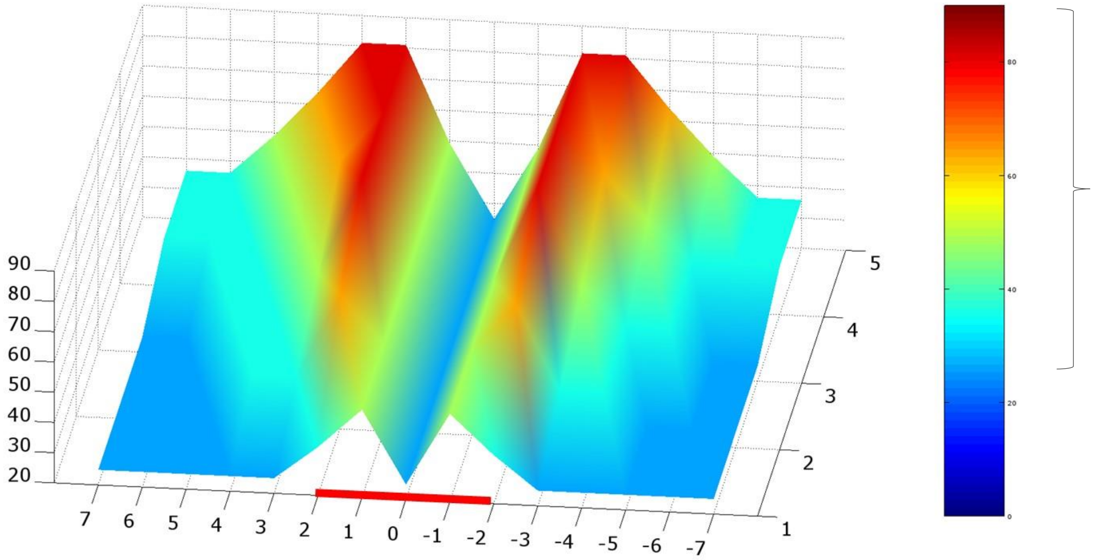




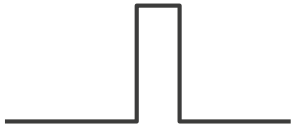
$$S(t) = D\cos(2\pi f_0 t) + D\frac{\sin(\pi D)}{(\pi D)}\left\{\cos\left[2\pi\left(f_0 - f_p\right)t\right] + \cos\left[2\pi\left(f_0 + f_p\right)t\right]\right\}$$

3. EXAMPLE

- Peak power gain
  - Evaluation: ± 5 m left/right array boundary, 1 - 5 m front, resolution 1 m



Range: 25 - 81

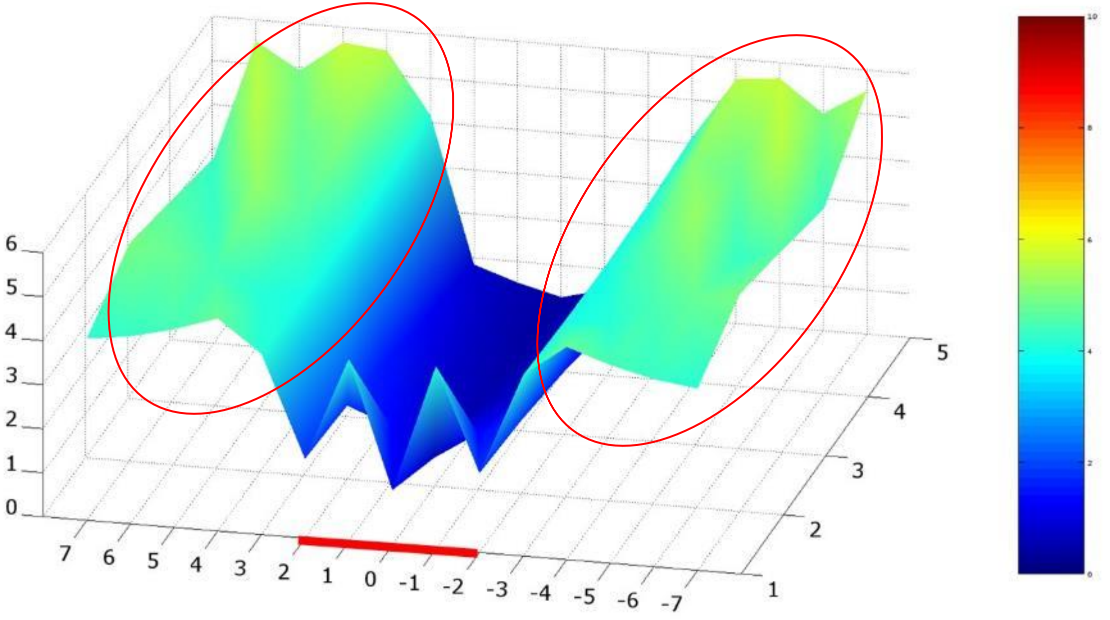


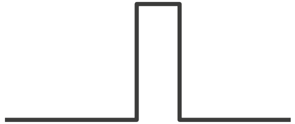
Perfect rectangular pulses

For most positions we cannot use all 9 elements satisfying T = 7.874 ns

3. EXAMPLE

- Average power gain
  - Evaluation: ± 5 m left/right array boundary, 1 -5 m front, resolution 1 m





Perfect rectangular pulses

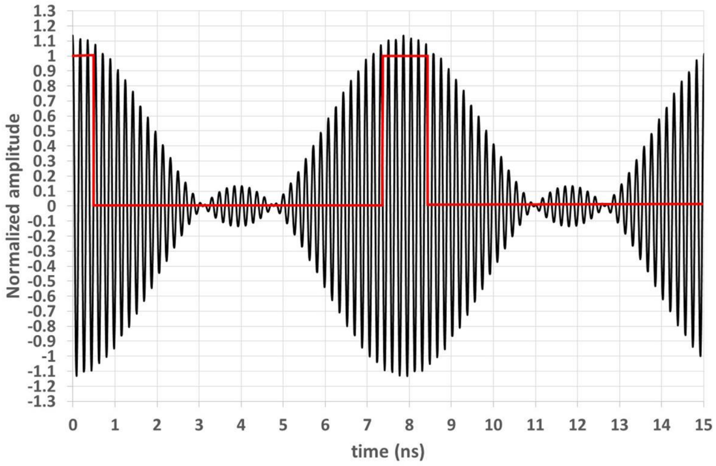
Range: 3.98-5.65

Range: 0.27-5.65

Rectifier needs to be part of analysis to investigate if/when peak power can compensate for average power

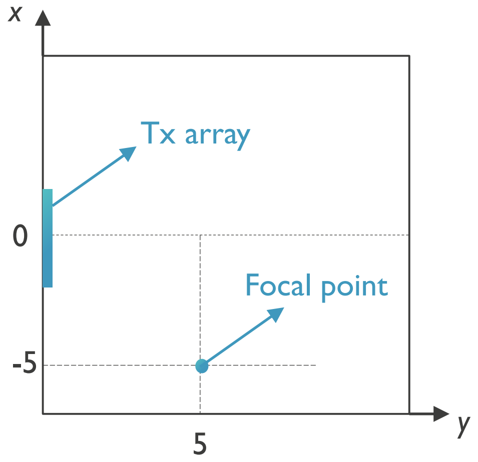
3. EXAMPLE

- Approximated rectangular pulses
  - Evaluation: (x_F, y_F) = (-5m, 5m)
  - 6 out 9 elements can be used



Element nr.	Time delay (ns)	Pulse width (ns)
0	0	1.207
1	1.207	1.258
2	2.465	1.301
3	3.766	1.339
4	5.105	1.372
5	6.477	1.397

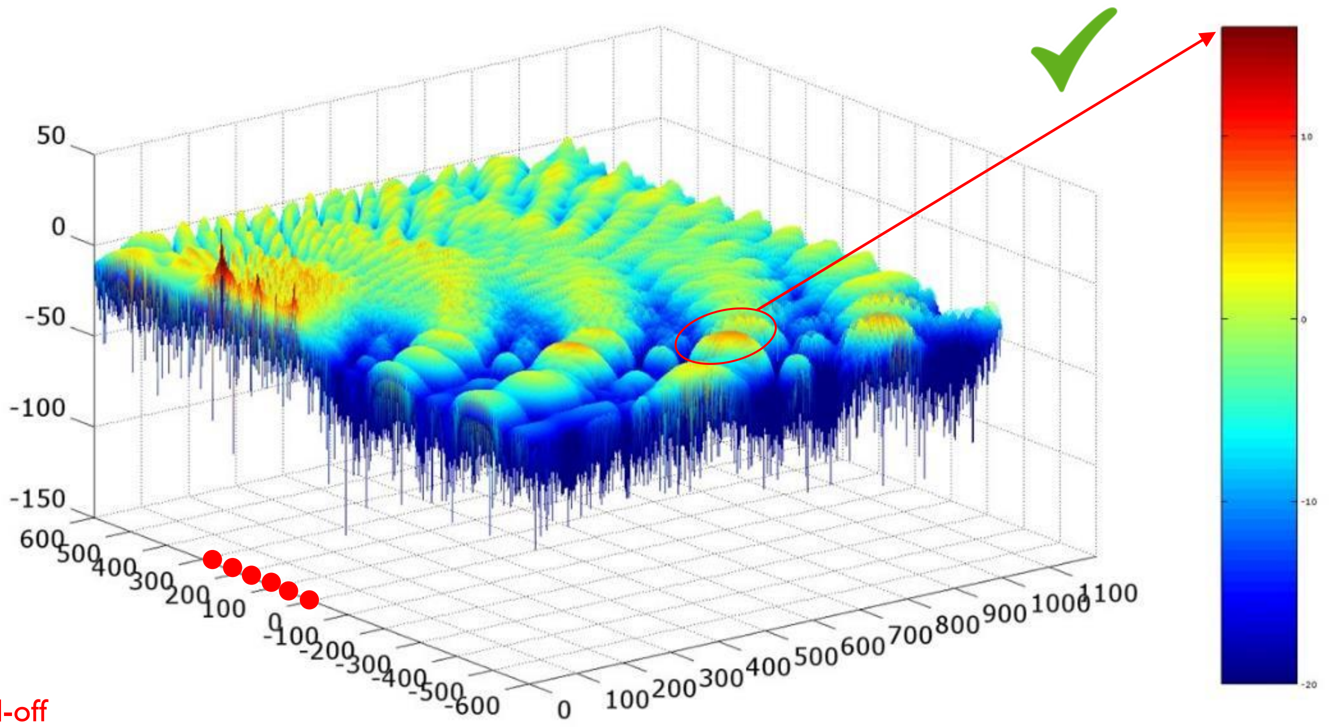
T_p = 7.874 ns



3. EXAMPLE

- Evaluation
  - 6 Tx elements
  - 0.5 m spacing
  - f_0=5.597 GHz
  - f_p=127 MHz
  - 3 spectral components for pulse
  - duty cycle = 0.16

POWER GAIN (dB)



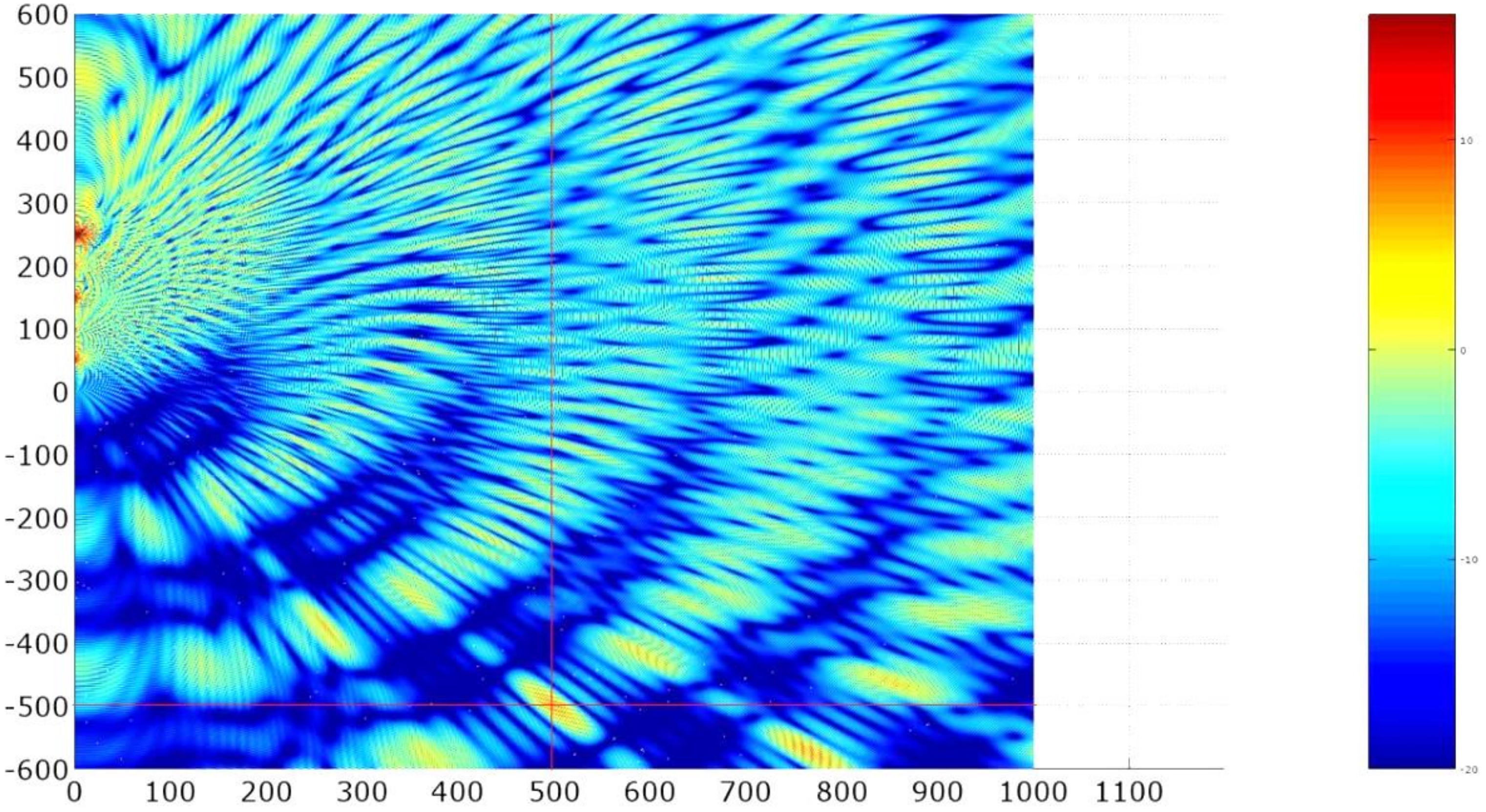
No $1/r^2$ power fall-off

3. EXAMPLE

- Evaluation

Power gain

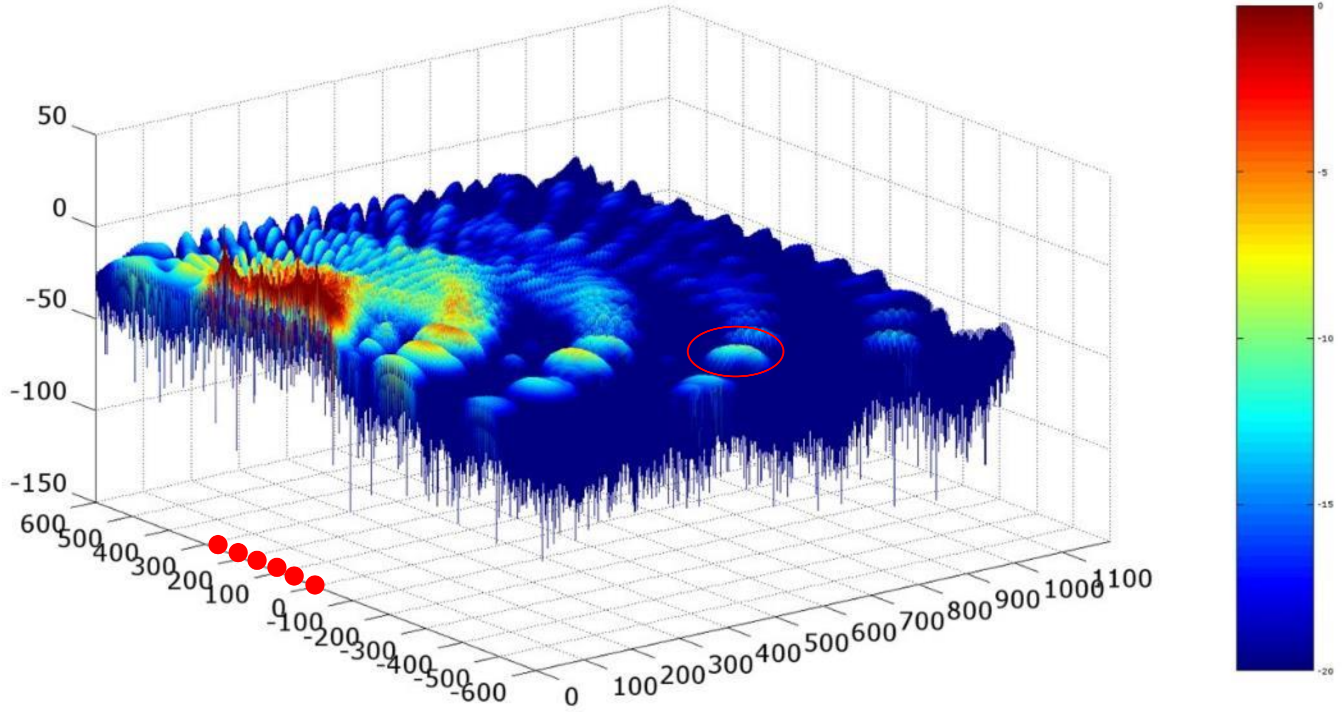
t = 0 ns



3. EXAMPLE

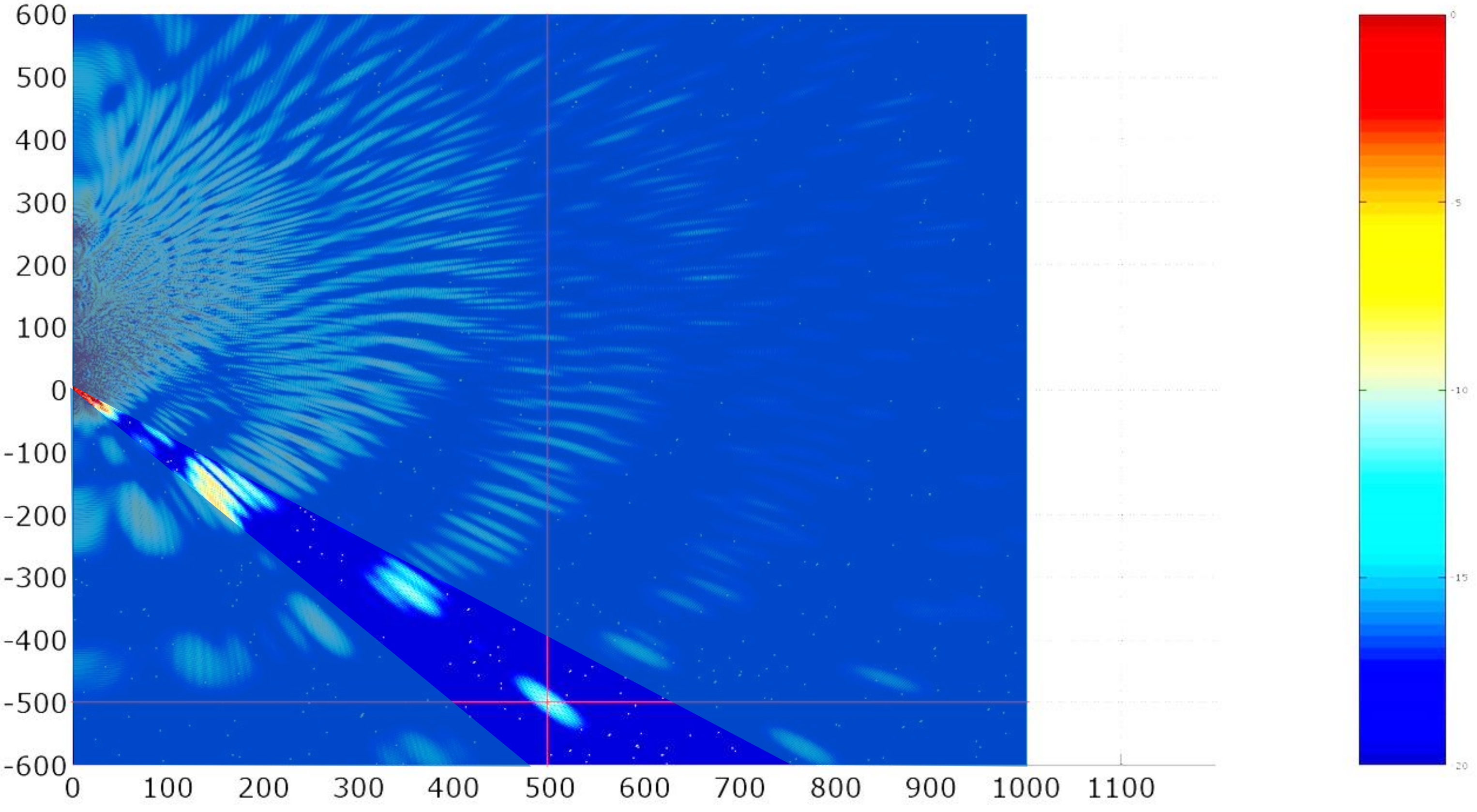
- Evaluation
  - $1/r^2$ power fall-off

POWER DROP (Path loss) (dB)



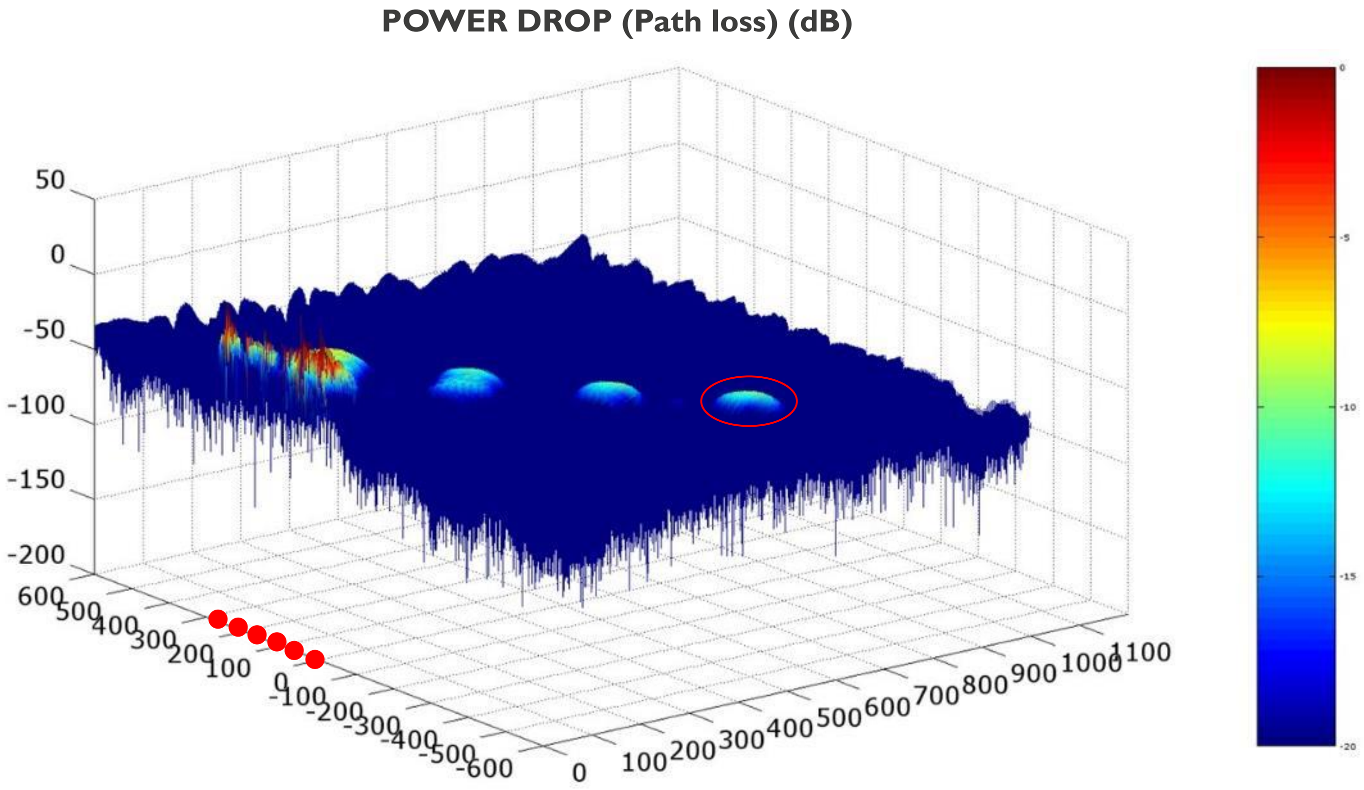
3. EXAMPLE

- Need for array



3. EXAMPLE

- Evaluation
  - Every radiator is replaced with a phased array antenna
  - 19 elements each
  - Spacing 2.7 cm
- Every phased array antenna is phased for beaming at the focal position.

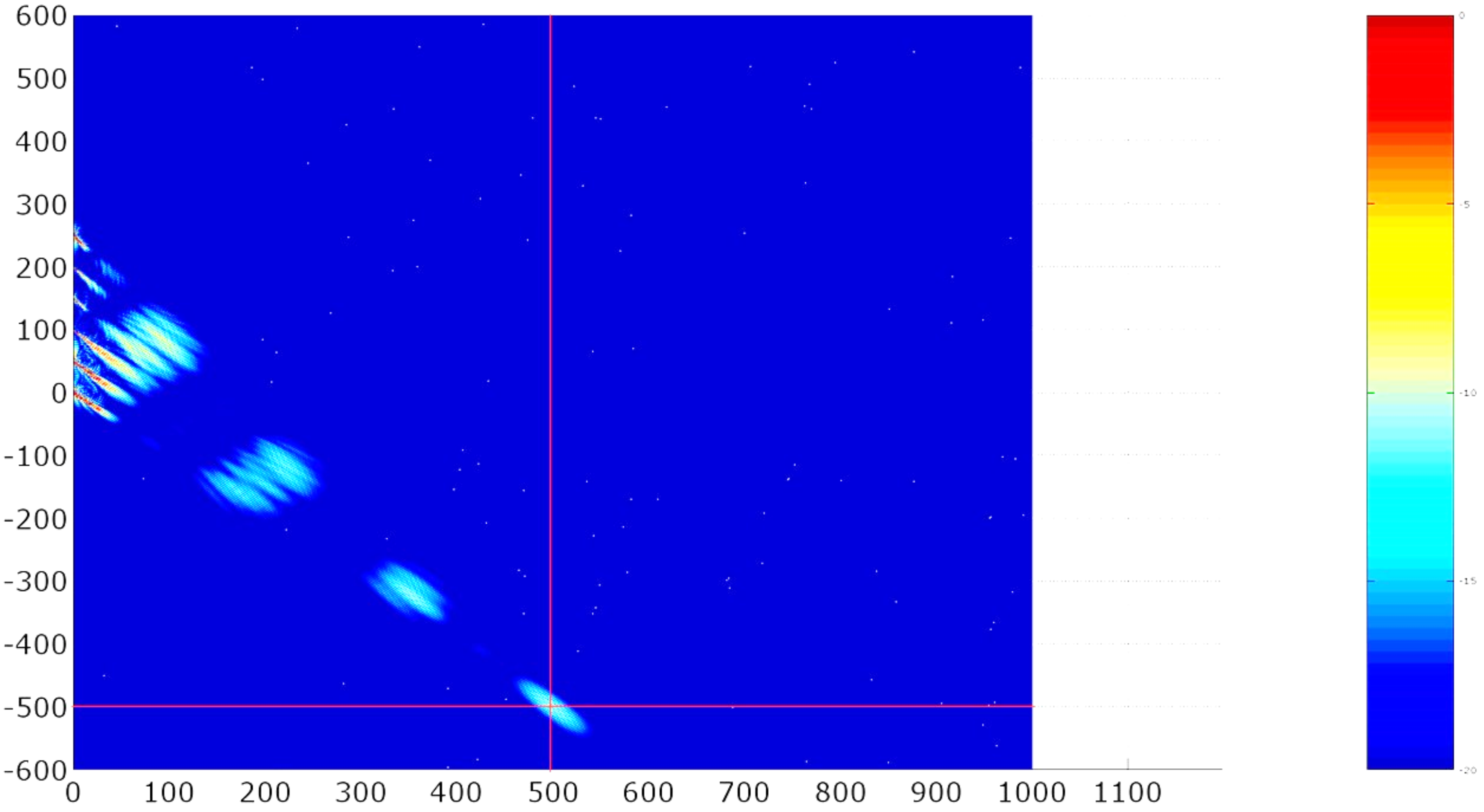


3. EXAMPLE

- Evaluation

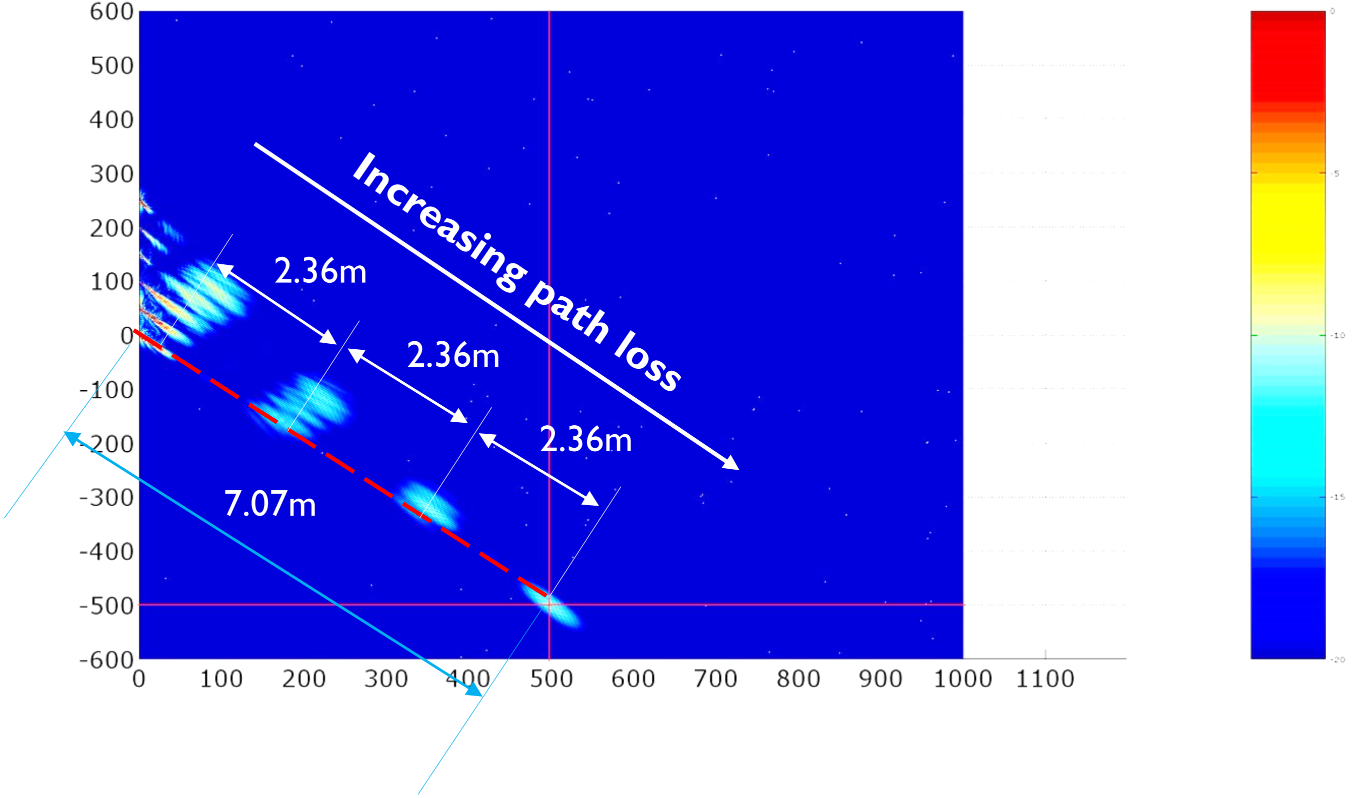
Power drop

t = 0.0 ns



3. EXAMPLE

- Evaluation
  - T = 1/127 μs
  - $T{*}c$ = 2.36 m

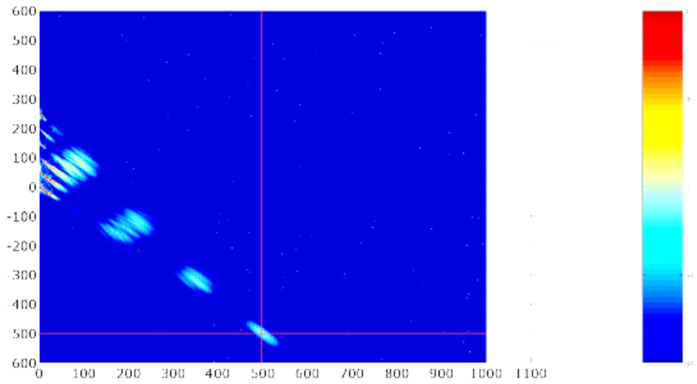


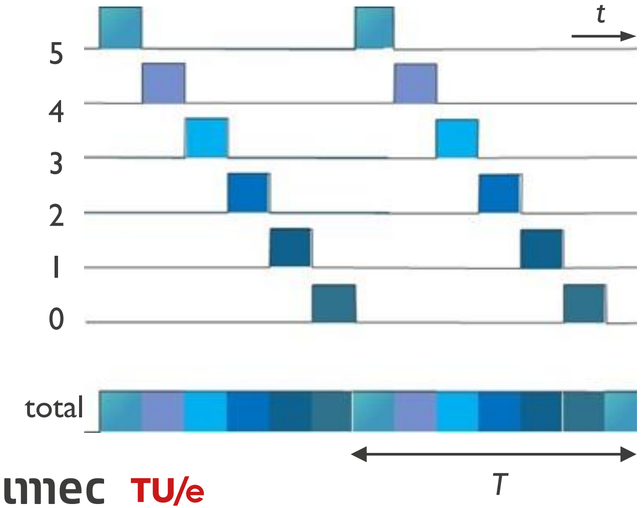
3. EXAMPLE

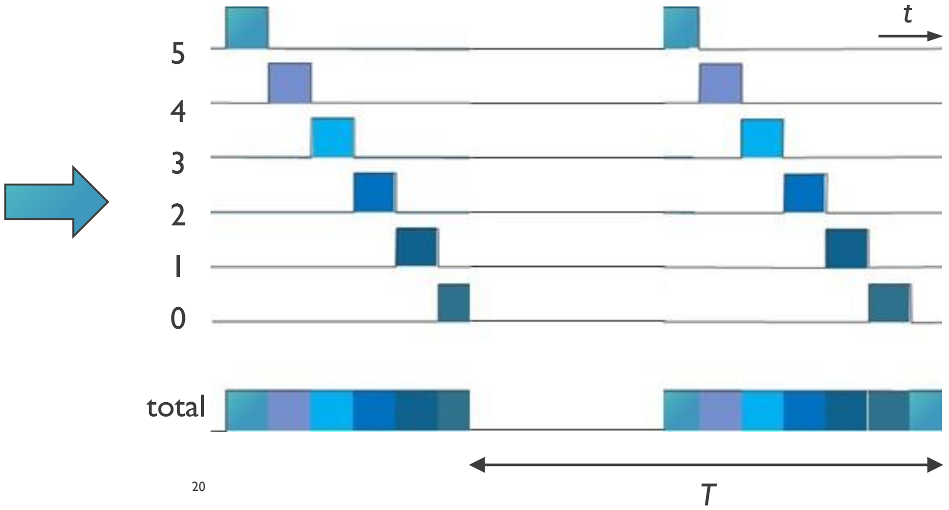
- Evaluation
  - Solution:
    Increase *T* and signal amplitude

T = 1/127 μs

<u>*Tc* = 2.36m</u>

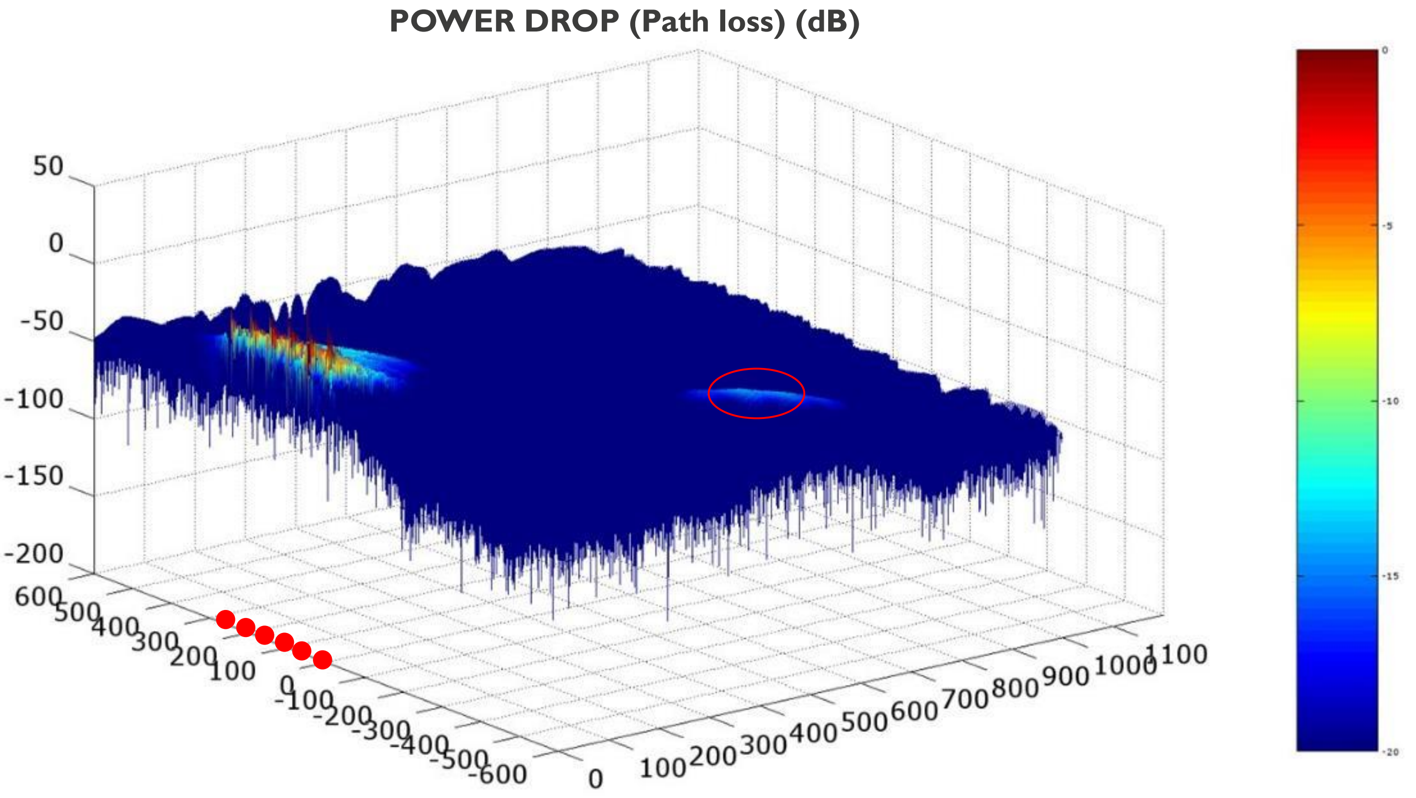






3. EXAMPLE

- Evaluation
  - Triple period

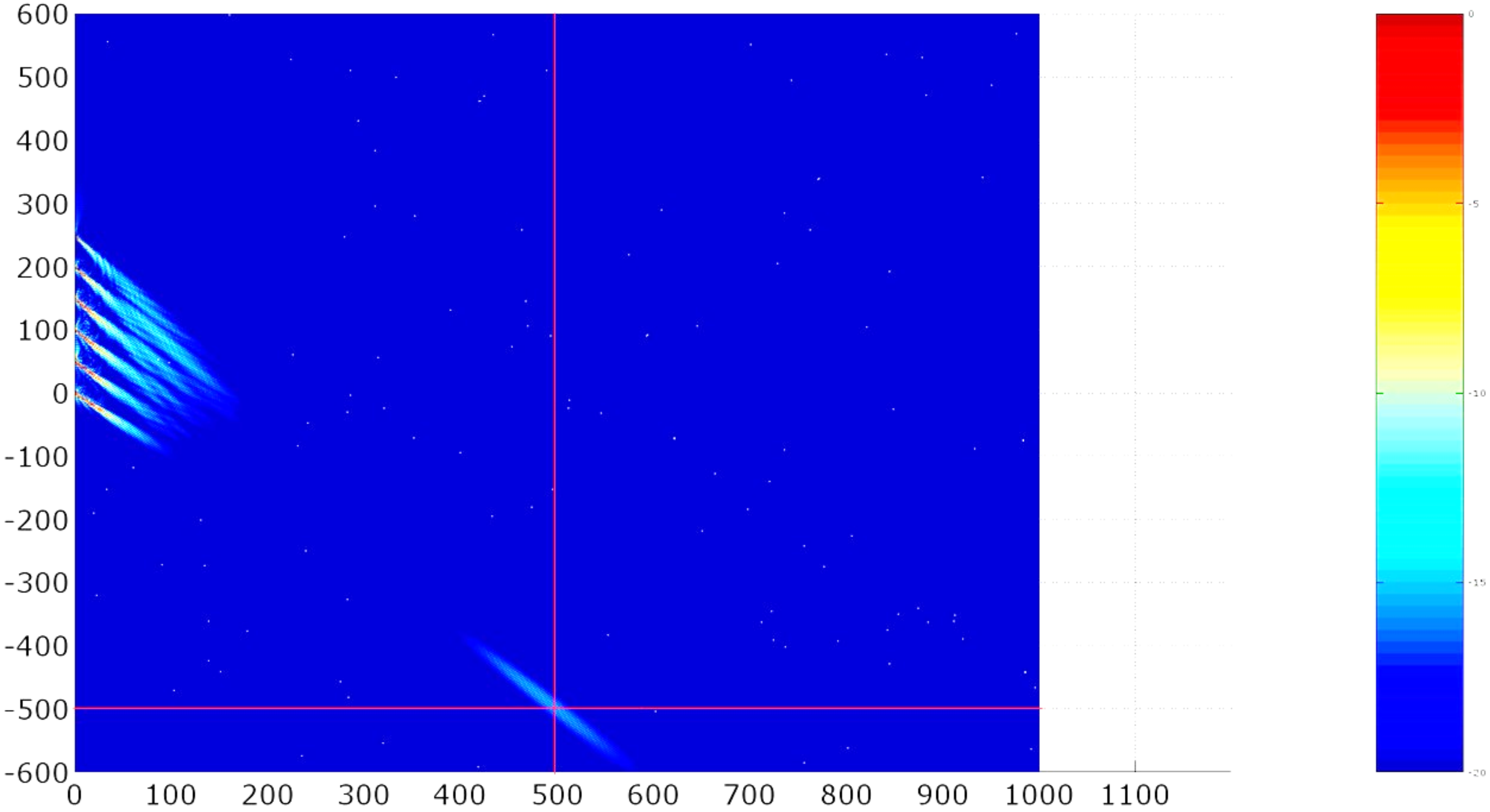


3. EXAMPLE

- Evaluation

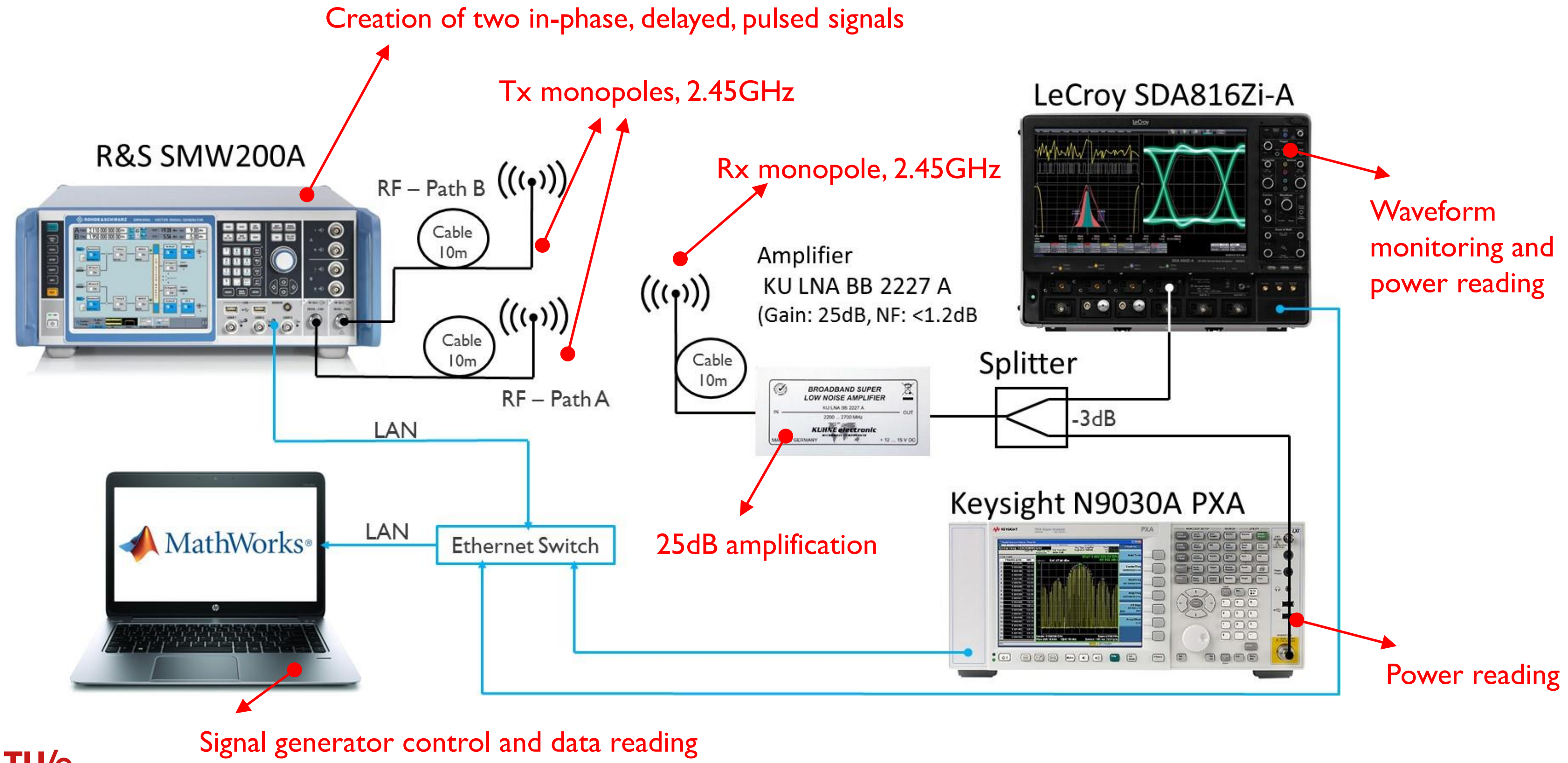
Power drop

t = 0.0 ns



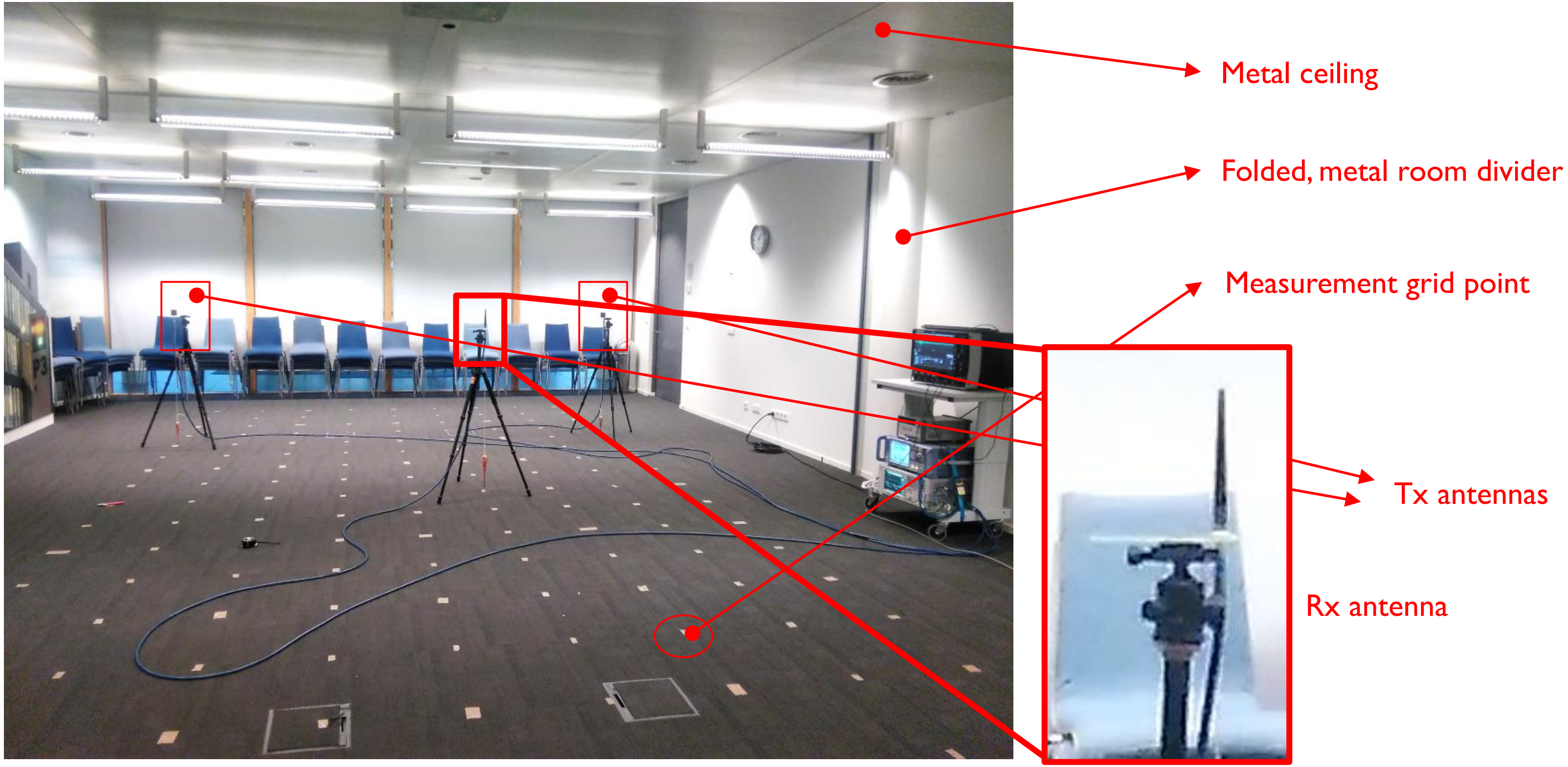
4. VALIDATION RESULTS

- Measurement setup



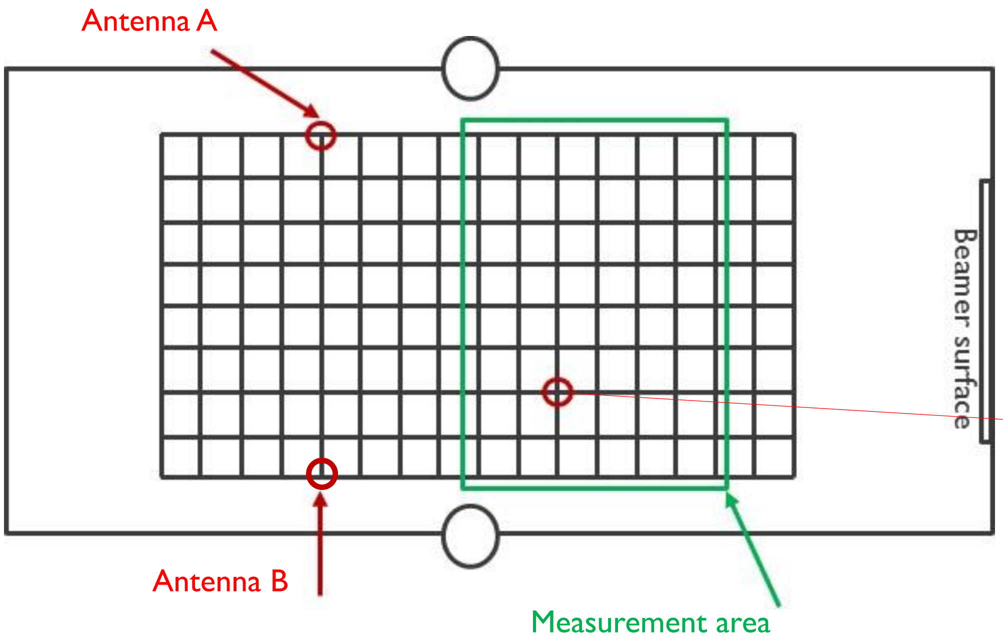
4. VALIDATION RESULTS

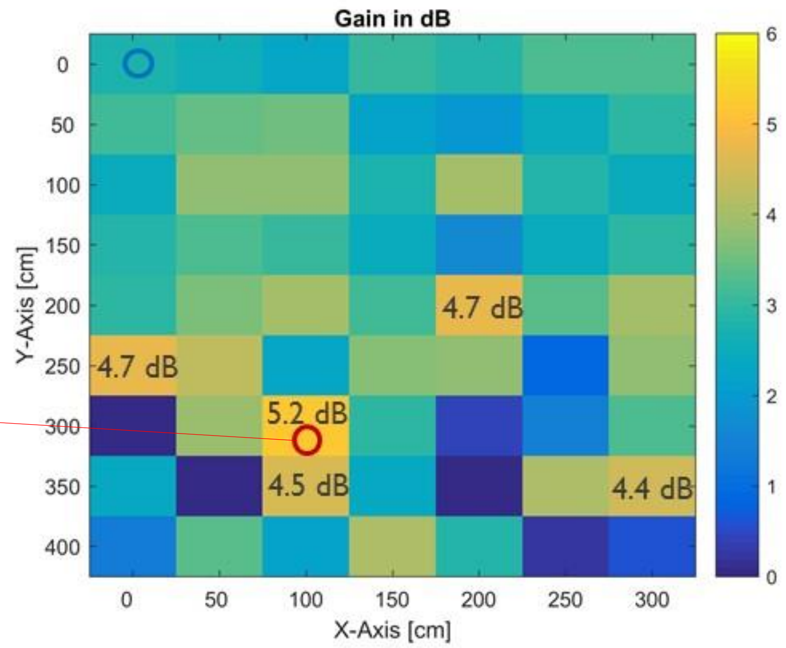
- Test set-up and measurement environment



4. VALIDATION RESULTS

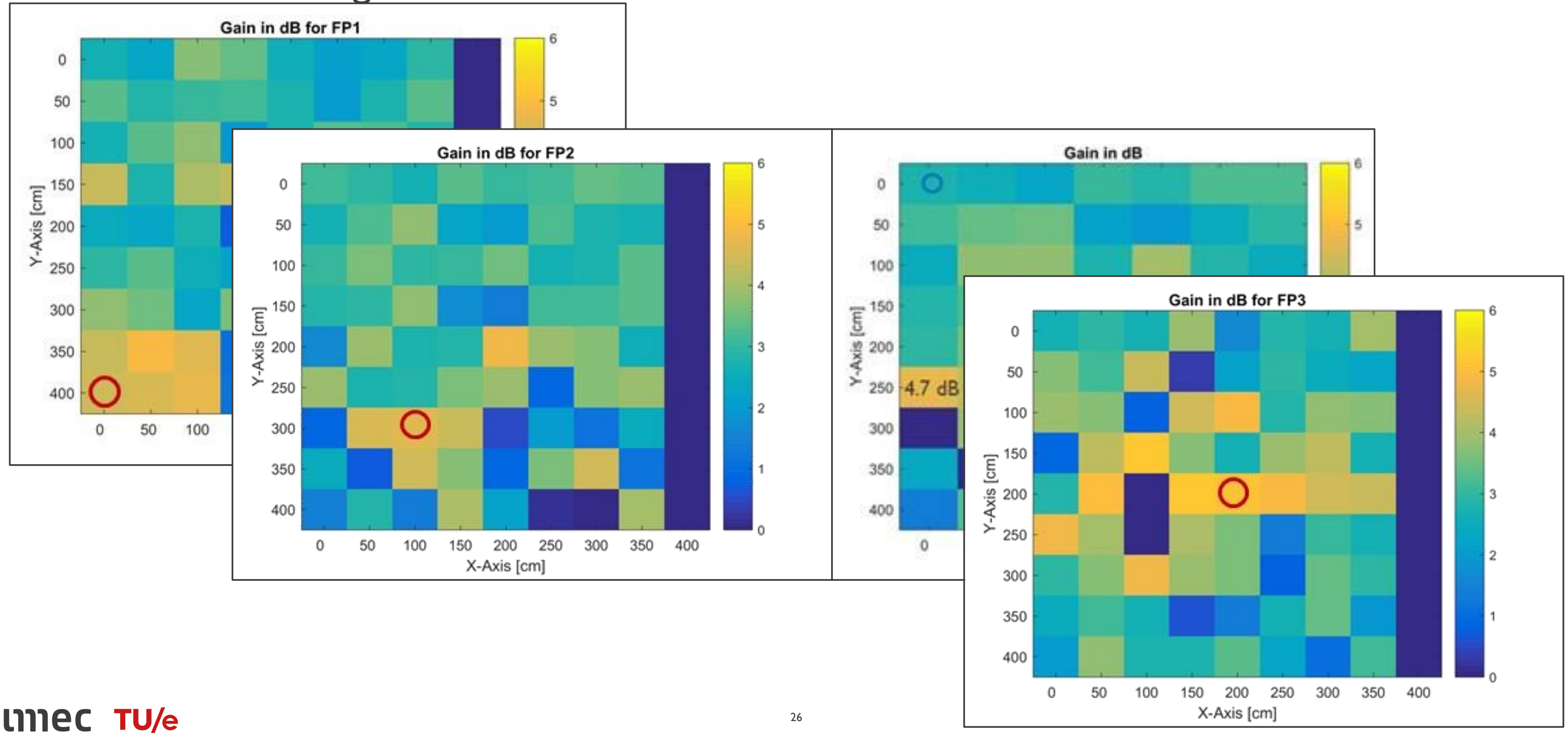
- Verification through measurement





4. VALIDATION RESULTS

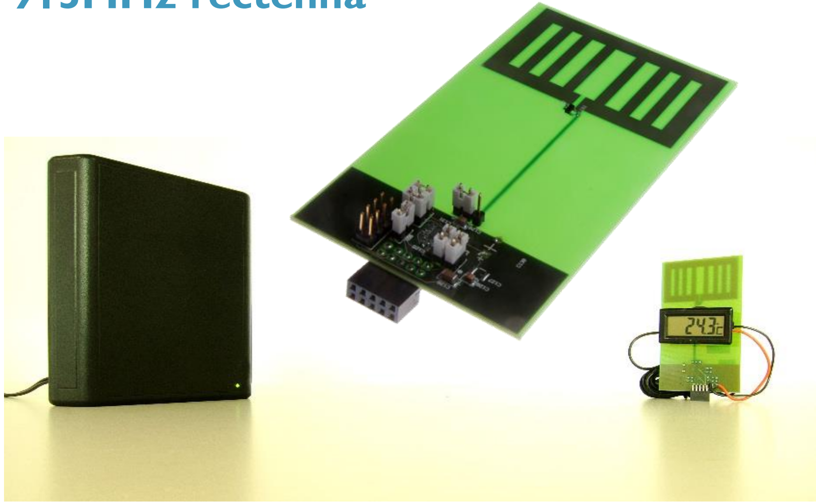
- Verification through measurement



5. EXPERIMENT: SWITCHING FOCAL POSITION

- Rectenna

915MHz rectenna



modification

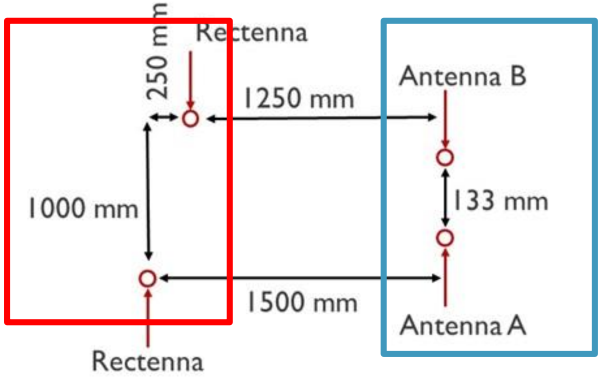
2.45 GHz Microstrip patch antenna

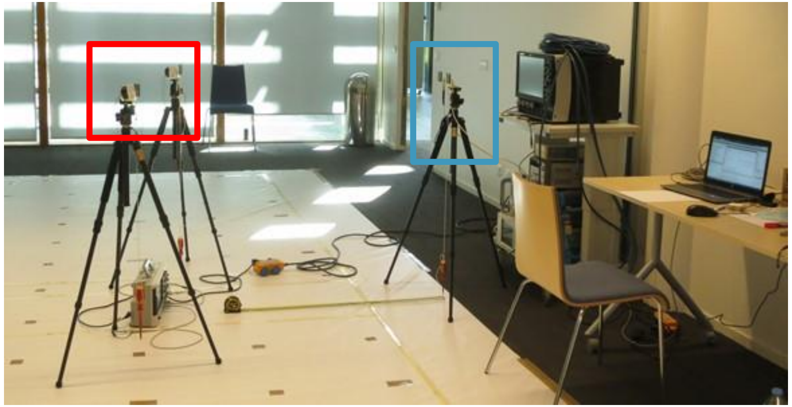
Rectenna optimized for -10dBm RF input power

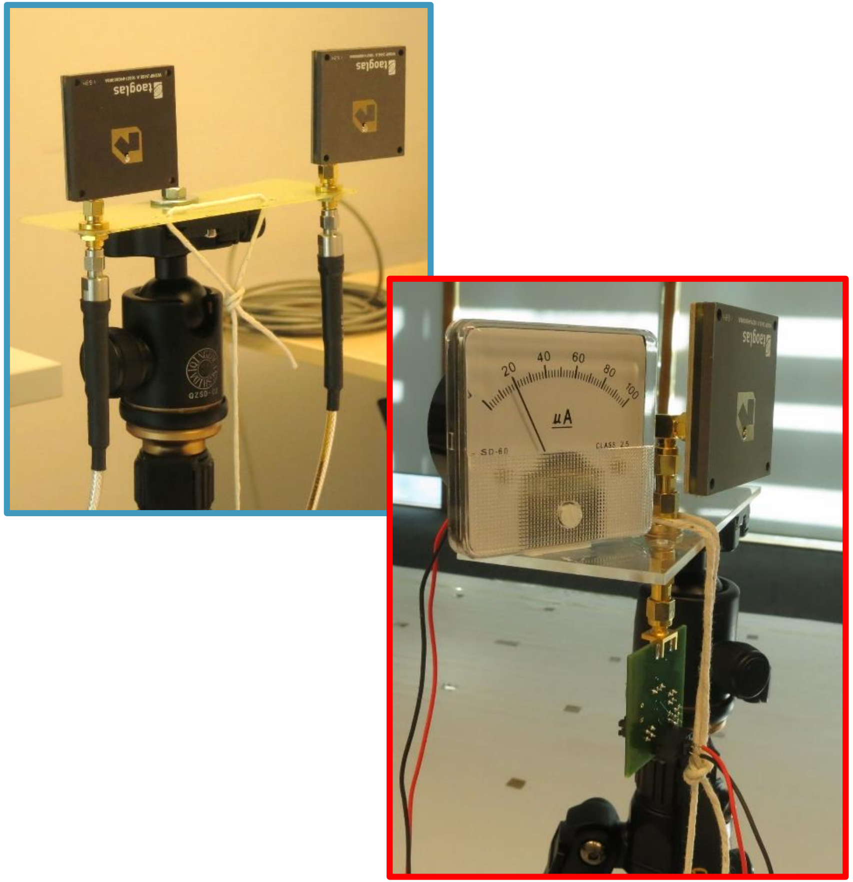
2.45 GHz rectifier and power management

5. EXPERIMENT: SWITCHING FOCAL POSITION

- Focal position switching







5. CONCLUSIONS

- High energy-density bubbles can be created by pulse-delayed excitation;
- In practice, use a pair of 'squinting' arrays;
- The theory of creating 'bubbles' of high RF energy density has been verified experimentally, using two transmitting monopole antennas;
- The power gain of an array of N elements, using time-delayed pulses can reach N^2;
- Using two directive transmit antennas, focal position switching has been demonstrated within a meter separation, delivering about 25μW DC power.

embracing a better life