Energy-efficient communication system based on nonlinear scattering of standard OFDM signals

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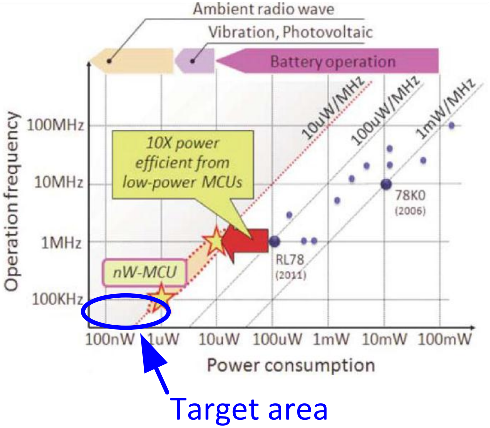
Miniaturized communication systems

- Data rate of several kbps.
- Distances between transmitter and receiver of 0.5 - 2 meters.
- Ultra low power consumption.
- **One of the main energy consumers in network nodes is RF transmitter.**



[1] Yoichi Yano, “Take the Expressway to go Greener”, *ISSCC*, 2012.

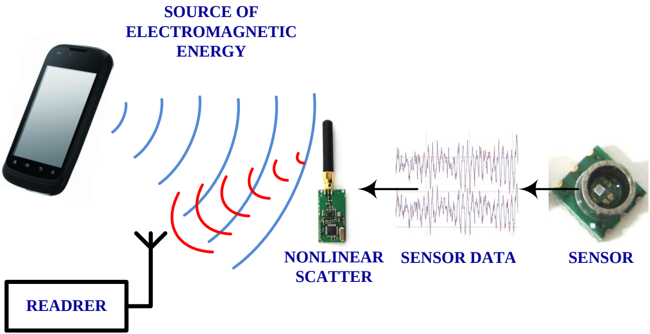
State-of-art

- In modern communication systems using external electromagnetic energy for data transmission commonly a specialized external source is applied.
- Usage of non-specialized sources such as standard OFDM transmitters of communication devices (e.g. mobile phones, Wi-Fi access points etc.) is a field of active research.
- One of the prospective principles in such systems is a nonlinear scattering.

Objective.

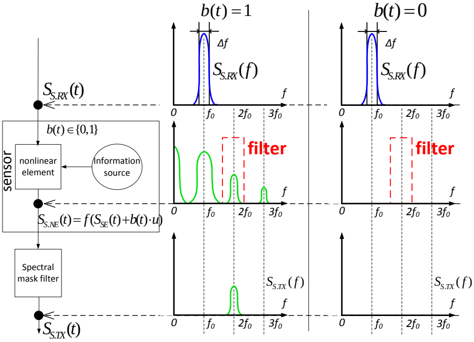
Analyzing potential characteristics of nonlinear scattering based transmitters in systems where OFDM signals are used as source of electromagnetic field.

Considered system configuration



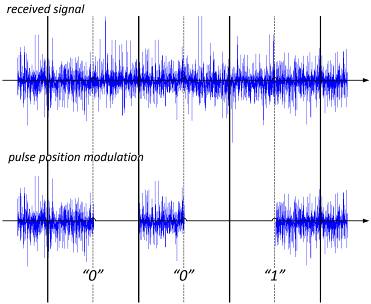
- OFDM signals are transmitted with standard communication devices (e.g. mobile phones, Wi-Fi access points etc.)
- Nonlinear nonlinear scatter reuse radiated energy for transmitting data from the sensor.
- Communication device can be used for data gathering from sensor, equipped with nonlinear scatter. Source of EE + Reader = **Terminal**.

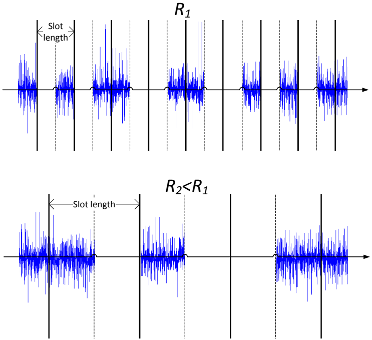
Nonlinear scattering effect



- When the nonlinear element is plugged, combination tones of received signal appear in a current going through antenna.
- **Second tone** is used, and others are rejected with a **filter**.

Pulse position modulation





- For data transmission we can only turn on or off signal.
- Pulse position-modulation (PPM) modulation - if bit value is 0 then the left subslot of the slot consists scattered signal, otherwise right subslot is used .
- Changing of the slot length leads to a changing of data rate.
- The greater the duration of the slots (and, therefore, less speed), the lower the Bit Error Rate.

According to radar range equation, power of signal received with sensor is:

$$P_{S.RX} = P_{e/m}\left(\frac{G_{e/m}}{4\pi r_0^2}\right)\left(\frac{G_S\lambda_1^2}{4\pi}\right)\left(\frac{r_0}{r_1}\right)^{\beta}$$

Taking into account losses in nonlinear scatter, sensor radiated power is:

$$P_{S.TX} = L \times P_{S.RX} = LP_{\mathrm{e/m}}\left(\frac{G_{\mathrm{e/m}}}{4\pi r_0^2}\right)\left(\frac{G_S\lambda_1^2}{4\pi}\right)\left(\frac{r_0}{r_1}\right)^{\beta}$$

Using the equation radar range equation for the second time, we find the power of signal received with reader:

$$P_{R.RX} = P_{S.TX}\left(\frac{G_S}{4\pi r_0^2}\right)\left(\frac{G_R\lambda_2^2}{4\pi}\right)\left(\frac{r_0}{r_2}\right)^{\beta} = \\ = P_{\mathrm{e/m}}\frac{LG_{\mathrm{e/m}}G_R\left(G_S\lambda_1\lambda_2\right)^2}{\left(4\pi r_0\right)^4}\left(\frac{r_0^2}{r_1 r_2}\right)^{\beta}$$

Link Budget 2/2

If the bit duration is equal to $\tau_b = {}^1\!/_R$ then the energy per bit is:

$$E_{R.TX} = \frac{1}{2}\frac{P_{\mathrm{e/m}} L G_{\mathrm{e/m}} G_R \left(G_S \lambda_1 \lambda_2\right)^2}{R\left(4\pi r_0\right)^4}\left(\frac{r_0^2}{r_1 r_2}\right)^\beta$$

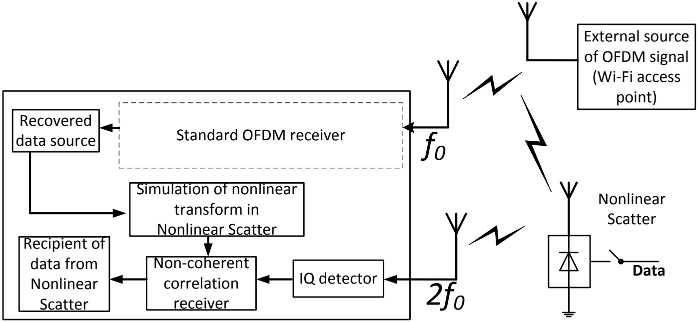
Here the factor 1/2 means that PPM modulation or on/off keying is used. Noise spectral density can be found with Boltzmann equation:

$$N_0 = kTK_n$$

Then the signal-to-noise ratio at the reader (as the ratio of energy per bit to noise power spectral density) is:

$$q_s = \frac{P_{\mathrm{e/m}} L G_{\mathrm{e/m}} G_R \left(G_S \lambda_1 \lambda_2\right)^2}{2kTK_n R\left(4\pi r_0\right)^4}\left(\frac{r_0^2}{r_1 r_2}\right)^\beta$$

Correlation receiver 1/2



- Reference signal is required.
- Reader receives OFDM symbols from external source, detects and decodes them and use for reference signal generation.

Used modulation scheme (PPM) is a scheme with orthogonal signals. Therefore, knowing the signal-to-noise ratio at the receiver reader we can estimate the bit error probability. It equals to:

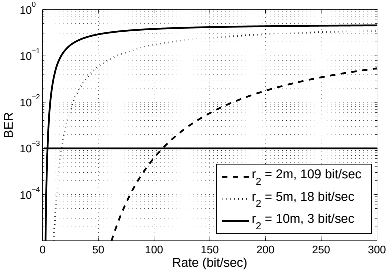
$$P_e = \frac{1}{2}\exp\left(-\frac{q_s}{2}\right)$$

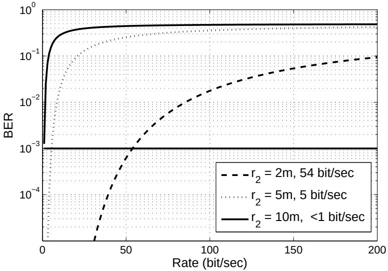
According to equation of SNR, the achievable data rate is

$$R = -\frac{P_{\mathrm{e/m}} L G_{\mathrm{e/m}} G_R \left(G_S \lambda_1 \lambda_2\right)^2}{2kTK_n \left(4\pi r_0\right)^4 2ln(2P_e)} \left(\frac{r_0^2}{r_1 r_2}\right)^{\beta}$$

Numerical example

- $G_{e/m} = 2.15$ dB, $G_S = 2.15$ dB, $G_R = 2.15$ (corresponds to half-wave dipole antenna);
- $K_n = 10$ dB (corresponds to typical receiver);
- $P_{e/m} = 100$ mW (corresponds to WiFi signal);
- $f_1 = 2.4$ GHz (corresponds to central frequency of WiFi signal);
- $f_2 = 4.8$ GHz (corresponds to second tone of nonlinearly transformed WiFi signal);
- $r_1 = 2$ m, $r_2 = [2, 5, 10]$ m;
- $\beta = [2, 2.5]$ path-loss factor.





Achieved data rates

- Uncoded channel throughput (with BER $= 10^{-3}$):

Distances* (m)	Data rate (kbps)
0.25	430
0.5	27
1	1.68
2	0.106

- Using a Hamming code (15,11) and 25% MAC overhead data rate up to 1 kbps can be achieved at distance 1m with BER $= 10^{-5}$.

(*) Distance between a Sensor and a terminal.

Conclusion

- We have proposed to use OFDM transmitters of standard communication devices as external source of electromagnetic field. Analysis allowed estimating of signal-to-noise ratio in such system.
- BER characteristics of nonlinear scatter system were calculated. By using correlation receiver if required bit-error ratio is 10^{-3} than data rate up to 109 bit/sec can be achieved for distance between source of e/m energy equal to 2 meter.

Further studies.

In further studies developments of multiple user access scheme for nonlinear scattering based transmitters and development of the synchronization scheme are planned.