Investigation of Modulation Techniques for Parametric Underwater Communications

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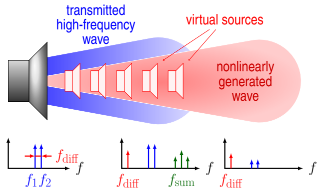
Motivation

- **approach:** exploit nonlinearly generated wave components for communication purposes
- **principle:** bases on the parametric array [1]:



- ○ transmission of a high-frequency acoustic wave
- ○ intermodulation within the transmitted wave during the wave propagation in fluid media
- → new frequency components are nonlinearly generated
- → low frequency components are used for communication purposes

- **key properties of the nonlinearly generated low frequency wave for underwater communications:**

  - \+ high directivity
    → mitigation of Doppler and delay spread
  - \+ low center frequency
    → longe-range communication
  - \+ high relative bandwidth
    → increase in data rate
  - \- conversion loss
    → longe-range communication
  - \- nonlinear signal distortions
    → requires specific modulation techniques

Physical Modelling

- fluid described by: ○ equilibrium state variables: p_0, ρ_0 and $\mathbf{v}_0$ (assumption: quiescent fluid $\mathbf{v}_0 = 0$)
  ○ disturbances: p, ρ and $\mathbf{v}$

- dependencies of these state variables are formulated in the basic set of equations (assumption: ideal fluid):

$$\frac{\partial \rho}{\partial t} = -\mathrm{div}\{(\rho_0+\rho)\,\mathbf{v}\} \qquad (1)$$
equation of continuity

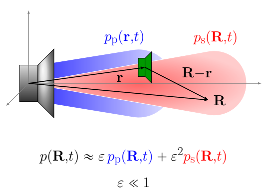
$$\frac{\partial}{\partial t}\Big\{(\rho_0+\rho)\,\mathbf{v}\Big\} + \Big(\mathrm{div}\Big\{(\rho_0+\rho)\mathbf{v}\cdot\mathbf{v}^{\mathrm{T}}\Big\}\Big)^{\mathrm{T}} + \mathrm{grad}\{p\} = 0 \qquad (2)$$
equation of motion

$$\rho = \mathrm{f}(p, p_0, \rho_0) \qquad (3)$$
equation of state (assumption: isentropic process)

- a second-order approximation of the basic set of equations followed by substitutions and manipulations gives:

$$\frac{1}{c_0^2}\frac{\partial^2 p(\mathbf{r},t)}{\partial t^2} - \Delta p(\mathbf{r},t) - \alpha\frac{\partial^2 p(\mathbf{r},t)^2}{\partial t^2} = 0$$

- a quasi-linear approach is considered to simplify the nonlinear second-order-wave equation:



$$p(\mathbf{R},t) \approx \varepsilon\, p_p(\mathbf{R},t) + \varepsilon^2 p_s(\mathbf{R},t)$$
$$\varepsilon \ll 1$$

- transmitted high frequency wave:
  - ○ denoted as primary wave p_p
  - ○ propagates approximately linearly
  - ○ creates virtual sources, which radiate the new frequency components
- nonlinearly generated frequency components:
  - ○ denoted as secondary wave p_s
  - ○ assumed to propagate linearly
  - ○ creates no further virtual sources

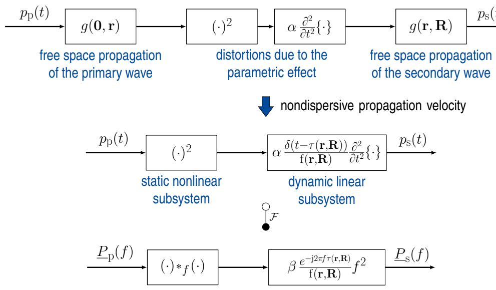
→ motivates the use of the perturbation theory

- using the perturbation theory and equating the coefficients yield two linear wave equations:
  - linear wave equation for the primary wave p_p:
  $$\frac{1}{c_0^2}\frac{\partial^2 p_p}{\partial t^2} - \Delta p_p = 0$$
  - linear, inhomogeneous wave equation for the secondary wave p_s:
  $$\frac{1}{c_0^2}\frac{\partial^2 p_s}{\partial t^2} - \Delta p_s = \alpha\frac{\partial^2 {p_p}^2}{\partial t^2}$$
- solution for the secondary wave with Green's function $g(\cdot)$:

$$p_s(\mathbf{R},t) = \int_V \alpha\frac{\partial^2 p_p(\mathbf{r},t)^2}{\partial t^2}\, g(\mathbf{R},\mathbf{r})\,\mathrm{d}\mathbf{r}$$

Channel Modelling

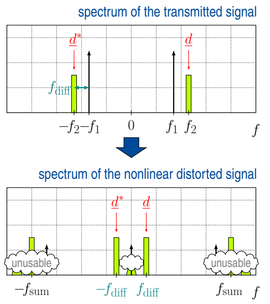
- the above discussed solution can be represented in a block-oriented channel model
- the consideration of only one virtual point source gives the channel model [2]:



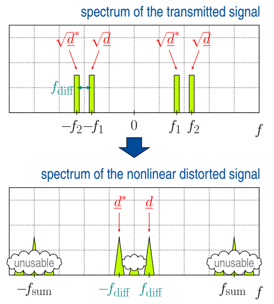
- **derived channel model:** → special case of the Hammerstein model
  → can be used in order to investigate modulation techniques

Modulation Techniques

- **conventional approach**



- **modulation by predistortion**

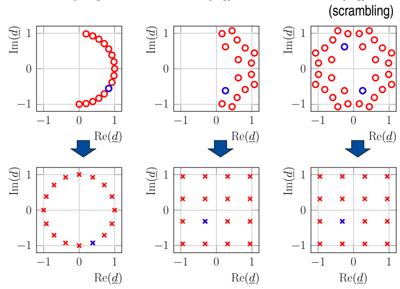


Constellations

- 16-PSK
- 16-QAM
- 16-QAM (scrambling)

transmitted constellations:

received constellations:



Conclusion

- the modulation techniques utilise the channel nonlinearity in order to generate conventional signal forms
- the modulation by predistortion outperforms the conventional approach for M-QAM schemes [3]
- both modulation techniques achieve the same performance for M-PSK schemes

[1] P. J. Westervelt: *Parametric Acoustic Array.* Journal of the Acoustical Society of America, vol. 35, no. 4, pp. 535–537, 1963.
[2] K. Wiedmann, T. Weber: *A Grey-Box Modelling Approach for the Nonlinear Parametric Channel.* IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP'14), pp. 4327–4331, Florence, Italy, 2014.
[3] K. Wiedmann, T. Weber: *Comparison of Modulation Techniques for Parametric Underwater Communications.* International Conference and Exhibition on Underwater Acoustics (UA2014), pp. 1443–1448, Rhodos, Greece, 2014.

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