Chaotic microwave systems based on traveling-wave tube (TWT) amplifiers

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Concept: Networks of coupled chaotic time-delayed oscillators (TDO)

- The radiation scattered off objects will couple in varying strengths to the various nodes of the network and modulate its dynamics.
Basic Research Questions

- How robust would synchronization in the network be in the presence of:
  - Noise
  - Mismatch in the dynamical parameters of the nodes
  - Interference or jamming
  - Complexity of the environment
Outline

- Basic characteristics of the traveling-wave tube (TWT)
- TWT nonlinearity
- Saturation models
- Results of previous simulations
- Results of experiments on TWT’s with time-delayed feedback
- Digital control of the time-delayed system
- Future research
TWT Basics

• Properties:
  High gain, wideband, good linearity and efficiency

• Applications:
  Space communications, secure LOS, cell phones, radar, EW

TWT Dispersion Diagram

Slow space charge wave

Slow EM wave

\[ \omega = k_z v \]
Typical characteristics of the TWTA

- High gain: 40-60 dB
- Wideband: >2 octaves
- Compact: m~ kg, L< 12 cm
- Efficient: >80% (Dep. Coll.)
- High Frequency: >50 GHz
- Modest Voltage: ~few kV
Nonlinearity in TWT’s (1-D Model)

RF field on helix

Modulated electron beam

Equation of Motion
\[ \frac{\partial v}{\partial t} = -\frac{v}{m} \frac{\partial v}{\partial z} - \frac{e}{m} \frac{\partial (V_w + V_{sc})}{\partial z} \]

Continuity
\[ \frac{\partial \rho}{\partial t} = -\frac{\partial (\rho v)}{\partial z} \]

Gauss’s Law
\[ \frac{\partial^2 V_{sc}}{\partial z^2} = -\frac{\rho}{\varepsilon_0} \]

Wave Equation
\[ \frac{\partial^2 V_w}{\partial t^2} - c^2 \frac{\partial^2 V_w}{\partial z^2} = cZ_0 A \frac{\partial^2 \rho}{\partial t^2} \]

Over-modulation of the beam increases space-charge forces which saturate the amplifier.
In some TWT’s, saturation is well described as a quadratic function of the input amplitude and the small-signal bandwidth as a first-order band pass filter (BPF).
Comparison of measured TWT drive curve with best fit to Saleh\textsuperscript{1} model

\[ y = A(r)e^{-j\Phi(r)} \]

\[ A(r) = \frac{\alpha_ar}{1 + \beta_ar^2} \]

\[ \Phi(r) = \frac{\alpha_\phi r^2}{(1 + \beta_\phi r^2)^2} \]

Model of a Time-delayed Feedback Oscillator Using Linear and Nonlinear Blocks to Describe the TWT

(see poster presented by Wai-Shing Lee)

Nonlinear Dynamics

Loop Gain: \[ k = \rho G_L \]

Output: \[ R(t) = A(t) \frac{e^{i\eta |A(t)|^2}}{1 + |A(t)|^2} \]

Dimensionless Time: \[ t \rightarrow t\Delta\omega, \tau \rightarrow \tau \Delta\omega \]

DDE: \[ \frac{dA(t)}{dt} + A(t) = kA(t - \tau) \frac{e^{i\eta |A(t-\tau)|^2}}{1 + |A(t-\tau)|^2} \]  

Quadratic Saturation Model
Numerical Results Using Quadratic Saturation Model

System Parameters: \( k = 7.142 \)
\( \tau = 0.530 \)
\( \eta = 1 \)

Characteristics of 276HA TWT Driver Amplifier for Satellite Communications

Frequency: 3-4 GHz
Output Power: 0.6 W
Gain: 35 dB
Bandwidth: 1 GHz
Efficiency: 70%

(Multi-Stage Depressed Collector Design)

Phase becomes periodic for large input amplitudes!
Time-delayed Feedback Oscillator Experiment (Wideband)

Model

\[ \eta = 1.0 \]
\[ \tau_{Norm} = 0.530 \]
\[ k = 7.142 \]

Experiment

\[ \eta = 3.4 \]
\[ \tau_{Norm} = (5\, ns)(2\pi \times 1\, GHz) = 10\pi \]
\[ \Phi \neq \text{quadratic function of } |A_{in}| \]

Caution: Our system has much longer memory!
Typical quasi-periodic behavior at low loop gains

Experimental results from an L-band TWT with a short feedback delay ($\tau_D = 20$ ns).
Full Band Case: Loop Gain, $k = 1.12$

- $|R(t)|$
- $|R(t-1.75\tau)|$
- Power Spectrum (dB)
- log(Correlation Coeff.)

Time (μs) vs. $|R(t)|$
Frequency (MHz) vs. Power Spectrum (dB)
Time Shift (μs) vs. log(Correlation Coeff.)
Loop Gain, $k = 1.41$

![Graphs showing loop gain, frequency spectrum, and correlation over time shift.](image-url)
Loop Gain, $k = 1.60$
Loop Gain, $k = 4.0$
Loop Gain, \( k = 7.94 \)
Deliverable: Develop an “dynamics package” that could be integrated into existing RF transmitters

- Simple construction
- Uses existing technology that is deployed in a wide variety of military systems.
- Generates power levels and frequencies that would be useful for covering wide areas (e.g. urban environments).
Digital control of dynamical states using quadrature feedback
Components of the dynamics control package
Digital Control of System State

• Adjustable loop gain/dynamics
• Apply new transfer functions to the feedback
• Automated setup of dynamics

\[ s = \pm I \pm iQ \]
\[ s = \overline{s} \]
\[ s = I^n \pm iQ^n \]
\[ s = I \rightarrow Q, Q \rightarrow I \]
Complex Feedback Transfer Functions

\[ S = \overline{S} \]

\[ \Delta \omega = 2\pi (40 \text{ MHz}) \]

\[ \tau_{\text{Norm}} = 1.25 \]

\[ k = 2.88 \]
$s = -s$

$\Delta \omega = 2\pi (40 \text{ MHz})$

$\tau_{\text{Norm}} = 1.25$

$k = 5.01$
\[ s = I - iQ \]

\[ \Delta \omega = 2\pi(40 \text{ MHz}) \]

\[ \tau_{\text{Norm}} = 1.25 \]

\[ k = 2.2, 5.01 \]
Transient chaos in a TWT (pulsed beam or feedback)

Very deep amplitude modulation
- Transients in TWT TDO’s

Time series of chaotic TWT output voltage (measured)
Summary of 2008 Results

• Basic characterization of TWT TDO’s at frequency bands relevant to Navy hardware:
  – L-band (1-2 GHz)
  – C-band (3-4 GHz)
  – X-band (8-12 GHz)
  – Ku-band (12-18 GHz)

• Demonstrated a simple method to control the state of the TWT TDO
  – Flexibility: the system can be adapted for various missions
Future Work (2009)

• Investigate synchronization in mutually coupled TWT TDO’s

• Construct a network of TWT devices
  – Demonstrate digital state control of the network
  – Study network dynamics w/ static coupling
  – TDO network dynamics when coupled through complex, time-dependent environments