Conversions Between $S$, $Z$, $Y$, $h$, $ABCD$, and $T$ Parameters which are Valid for Complex Source and Load Impedances

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Abstract—This paper provides tables which contain the conversion between the various common two-port parameters, $Z$, $Y$, $h$, $ABCD$, $S$, and $T$. The conversion are valid for complex normalizing impedances. An example is provided which verifies the conversions to and from $S$ parameters.

I. INTRODUCTION

Most microwave textbooks these days seem to provide a table of the conversion between the various 2-port parameters. These 2-port parameters often include $Z$ (impedance), $Y$ (admittance), $h$ (hybrid), $ABCD$ (chain), $S$ (scattering), and $T$ (chain scattering or chain transfer). While the scattering parameters have been shown [1] to be valid for complex normalizing impedances (with positive real parts), the tables in [2]-[15] are not valid for complex source and load impedances. Often, the tables only provide conversions for the cases where port 1 and port 2 normalizing impedances are equal, i.e., $Z_{01} = Z_{02} = Z_0$. Some have results in which $Z_{01}$ and $Z_{02}$ are normalized to 1. Others provide equations for port 1 and port 2 impedances $Z_{01}$ and $Z_{02}$ to be unique. However, in all of these cases, the results are not valid when the impedances, $Z_{01}$ and $Z_{02}$, or just $Z_0$, are complex.

Of the two-port parameters mentioned, only the $S$ and $T$ parameters are dependent upon the source and load impedances. In this paper, the derivations of the conversions from the $S$ and $T$ parameters to the other 2-port parameters includes complex source and load impedances. The equations developed in this work are valid with port 1 and port 2 normalizing impedances complex and unique. When the normalizing impedances are real, the results simplify to those shown in other references. To make the list complete, the conversions between the $Z$, $Y$, $h$, and $ABCD$ parameters as well as between $S$ and $T$ parameters are included.

II. DERIVATION

Two-port parameters are defined for a general 2-port network as shown in Fig. 1. Using the voltages and currents defined in this figure, the various 2-port parameters are written as

$$V_1 = Z_{11} \cdot I_1 + Z_{12} \cdot I_2 \tag{1a}$$

$$V_2 = Z_{21} \cdot I_1 + Z_{22} \cdot I_2 \tag{1b}$$

$$I_1 = Y_{11} \cdot V_1 + Y_{12} \cdot V_2 \tag{2a}$$

$$I_2 = Y_{21} \cdot V_1 + Y_{22} \cdot V_2 \tag{2b}$$

$$I_1 = h_{11} \cdot I_1 + h_{12} \cdot V_2 \tag{3a}$$

$$I_2 = h_{21} \cdot I_1 + h_{22} \cdot V_2 \tag{3b}$$

$$V_1 = A \cdot V_2 - B \cdot I_2 \tag{4a}$$

$$I_1 = C \cdot V_2 - D \cdot I_2 \tag{4b}$$

$$b_1 = S_{11} \cdot a_1 + S_{12} \cdot a_2 \tag{5a}$$

$$b_2 = S_{21} \cdot a_1 + S_{22} \cdot a_2 \tag{5b}$$

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Fig. 2. A general two-port network with a's and b's defined.

where * indicates complex conjugate and $Z_{0j}$ is the normalizing impedance for the jth port. For two-port networks, $Z_{01}$ and $Z_{02}$ are the source and load impedances of the system in which the $S$ parameters of the two-port are measured or calculated. $I_{ij}$ and $I_{jr}$ are the incident and reflected currents for the jth port. Knowing that,

$$I_j = I_{ji} - I_{jr}$$  \hspace{1cm} (8)\\

we can solve (7a) and (7b) for $I_{ji}$ and $I_{jr}$ and substitute them into (8) to get,

$$I_j = \left[ \frac{2}{Z_{0j} + Z_{0j}^*} \right]^{1/2} \cdot (a_j - b_j).$$  \hspace{1cm} (9)\\

Knowing also that,

$$V_j = V_{ji} + V_{jr}$$  \hspace{1cm} (10)\\

where $V_{ji}$ and $V_{jr}$ are the incident and reflected voltage at the jth port, we can substitute the expressions for $I_{ji}$ and $I_{jr}$ along with

$$V_{ji} = I_{ji} \cdot Z_{0j}^*$$

$$V_{jr} = I_{jr} \cdot Z_{0j}$$

into (10) to get,

$$V_j = \left[ \frac{2}{Z_{0j} + Z_{0j}^*} \right]^{1/2} \cdot (a_j \cdot Z_{0j}^* + b_j \cdot Z_{0j}).$$  \hspace{1cm} (11)
TABLE II

EQUATIONS FOR THE CONVERSION BETWEEN \( T \) PARAMETERS AND \( Z, Y, h, \) AND \( ABCD \) PARAMETERS WITH A SOURCE IMPEDANCE \( Z_01 \) AND LOAD IMPEDANCE \( Z_02 \)

\[
\begin{align*}
T_{11} &= \frac{(\frac{1}{Z_01} + \frac{1}{Z_02})}{2Z_01Z_02} \\
T_{12} &= \frac{Z_02 - Z_01}{2Z_01Z_02} \frac{1}{2} \\
T_{21} &= \frac{Z_01 - Z_02}{2Z_01Z_02} \frac{1}{2} \\
T_{22} &= \frac{Z_01 + Z_02}{2Z_01Z_02} \frac{1}{2}
\end{align*}
\]

\[\begin{align*}
Z_{11} &= \frac{Z_01T_{11} + T_{21}}{T_{11} + T_{21}} \\
Z_{12} &= \frac{Z_02T_{21} + T_{22}}{T_{11} + T_{21}} \\
Z_{21} &= \frac{Z_01T_{11} + T_{12}}{T_{11} + T_{22}} \\
Z_{22} &= \frac{Z_02T_{22} + T_{21}}{T_{11} + T_{22}}
\end{align*}\]

Solving (9) and (11) for \( a_j \) and \( b_j \) gives

\[
\begin{align*}
a_j &= \frac{V_j + Z_0jI_j}{[2(Z_0j + Z_0j)]^{1/2}} \quad (12) \\
b_j &= \frac{V_j - Z_0jI_j}{[2(Z_0j + Z_0j)]^{1/2}} \quad (13)
\end{align*}
\]

Equations (12) and (13) are (3) and (4) in [1] and serve as the starting point.

The notation, \( S \leftrightarrow Z \), indicates the conversion from \( S \) parameters to \( Z \) parameters and \( Z \) parameters to \( S \) parameters. Since \( S \) and \( T \) parameters are defined in terms of \( a \)'s and \( b \)'s, they will contain the source and load normalizing impedances \( Z_01 \) and \( Z_02 \). The other 2-port parameters are defined independent of the source and load impedances.

To derive the conversions, \( S \leftrightarrow Z \), \( S \leftrightarrow Y \), \( S \leftrightarrow h \), \( S \leftrightarrow ABCD \), \( T \leftrightarrow Z \), \( T \leftrightarrow Y \), \( T \leftrightarrow h \), and \( T \leftrightarrow ABCD \), it is necessary to use (9), (11)–(13). For example, to derive the expressions for \( S \) parameters in terms of the \( Z \) parameters, first substitute (9) and (11) into (1a) and (1b) and solve for \( b_1 \) and \( b_2 \) to get in the form of (5a) and (5b). Likewise, to get the expressions for the \( Z \) parameters in terms of the \( S \) parameters, substitute (12) and (13) into (5a) and (5b) and solve for \( V_1 \) and \( V_2 \) to get in the form of (1a) and (1b).

Since \( Z \), \( Y \), \( h \), and \( ABCD \) parameters do not require normalizing impedances, the conversions, \( Z \leftrightarrow Y \), \( Z \leftrightarrow h \), \( Z \leftrightarrow ABCD \), and \( h \leftrightarrow ABCD \), as well as \( S \leftrightarrow T \), are straightforward. These conversions are accomplished by rearranging one set of equations into the form of the other. These conversions appear in many of the references cited and are included here for completeness.

III. RESULTS

The results are given in the following tables. In these tables, \( Z_01 \) and \( Z_02 \) are the source and load impedances of the system to which the \( S \) and \( T \) parameters pertain. Complex conjugate is indicated by *, and \( R_01 \) and \( R_02 \) are the real parts of \( Z_01 \) and \( Z_02 \).

Table I gives the conversions between \( S \) parameters and \( Z \), \( Y \), \( h \), and \( ABCD \) parameters. Table II gives the conversions...
### Table III

Equations for the conversion between S parameters and normalized Z, Y, h, and ABCD parameters with a source impedance $Z_{01}$ and load impedance $Z_{02}$

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{11}$</td>
<td>$\frac{S_{11} - S_{21}}{2}$</td>
<td>$Z_{11} = \frac{Z_{11} + (S_{12} + S_{21})}{(Z_{11} + (S_{12} + S_{21}))}$</td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>$\frac{S_{12} + S_{21}}{2}$</td>
<td>$Z_{12} = \frac{Z_{12}}{(S_{12} + S_{21})}$</td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>$\frac{S_{21}}{2}$</td>
<td>$Z_{21} = \frac{Z_{21}}{S_{21}}$</td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>$\frac{S_{22}}{2}$</td>
<td>$Z_{22} = \frac{Z_{22}}{S_{22}}$</td>
</tr>
</tbody>
</table>

**Y Parameters**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{11}$</td>
<td>$\frac{Y_{11} - Y_{21}}{2}$</td>
<td>$Y_{11} = \frac{Y_{11} + Y_{21}}{Y_{11} + Y_{21}}$</td>
</tr>
<tr>
<td>$Y_{12}$</td>
<td>$\frac{Y_{12} + Y_{21}}{2}$</td>
<td>$Y_{12} = \frac{Y_{12} + Y_{21}}{Y_{12} + Y_{21}}$</td>
</tr>
<tr>
<td>$Y_{21}$</td>
<td>$\frac{Y_{21}}{2}$</td>
<td>$Y_{21} = \frac{Y_{21}}{Y_{21}}$</td>
</tr>
<tr>
<td>$Y_{22}$</td>
<td>$\frac{Y_{22}}{2}$</td>
<td>$Y_{22} = \frac{Y_{22}}{Y_{22}}$</td>
</tr>
</tbody>
</table>

**h Parameters**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{11}$</td>
<td>$\frac{h_{11} + h_{22}}{2}$</td>
<td>$h_{11} = \frac{h_{11} + h_{22}}{h_{11} + h_{22}}$</td>
</tr>
<tr>
<td>$h_{12}$</td>
<td>$\frac{h_{12}}{2}$</td>
<td>$h_{12} = \frac{h_{12}}{h_{12}}$</td>
</tr>
<tr>
<td>$h_{21}$</td>
<td>$\frac{h_{21}}{2}$</td>
<td>$h_{21} = \frac{h_{21}}{h_{21}}$</td>
</tr>
<tr>
<td>$h_{22}$</td>
<td>$\frac{h_{22}}{2}$</td>
<td>$h_{22} = \frac{h_{22}}{h_{22}}$</td>
</tr>
</tbody>
</table>

**ABCD Parameters**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>$A_{11} + B_{11} - C_{11} - D_{11}$</td>
<td>$A = \frac{A_{11} + B_{11} - C_{11} - D_{11}}{A_{11} + B_{11} - C_{11} - D_{11}}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$A_{11} + B_{11} - C_{11} - D_{11}$</td>
<td>$B = \frac{A_{11} + B_{11} - C_{11} - D_{11}}{A_{11} + B_{11} - C_{11} - D_{11}}$</td>
</tr>
<tr>
<td>$C$</td>
<td>$A_{11} + B_{11} - C_{11} - D_{11}$</td>
<td>$C = \frac{A_{11} + B_{11} - C_{11} - D_{11}}{A_{11} + B_{11} - C_{11} - D_{11}}$</td>
</tr>
<tr>
<td>$D$</td>
<td>$A_{11} + B_{11} - C_{11} - D_{11}$</td>
<td>$D = \frac{A_{11} + B_{11} - C_{11} - D_{11}}{A_{11} + B_{11} - C_{11} - D_{11}}$</td>
</tr>
</tbody>
</table>

**S Parameters**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{11}$</td>
<td>$\frac{Z_{11} + (S_{12} + S_{21})}{Z_{11} + (S_{12} + S_{21})}$</td>
<td>$S_{11} = \frac{Z_{11} + (S_{12} + S_{21})}{Z_{11} + (S_{12} + S_{21})}$</td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>$\frac{Z_{12}}{Z_{12}}$</td>
<td>$S_{12} = \frac{Z_{12}}{Z_{12}}$</td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>$\frac{Z_{21}}{Z_{21}}$</td>
<td>$S_{21} = \frac{Z_{21}}{Z_{21}}$</td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>$\frac{Z_{22}}{Z_{22}}$</td>
<td>$S_{22} = \frac{Z_{22}}{Z_{22}}$</td>
</tr>
</tbody>
</table>

**Z Parameters**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{11}$</td>
<td>$\frac{Z_{11} + (S_{12} + S_{21})}{Z_{11} + (S_{12} + S_{21})}$</td>
<td>$Z_{11} = \frac{Z_{11} + (S_{12} + S_{21})}{Z_{11} + (S_{12} + S_{21})}$</td>
</tr>
<tr>
<td>$Z_{12}$</td>
<td>$\frac{Z_{12}}{Z_{12}}$</td>
<td>$Z_{12} = \frac{Z_{12}}{Z_{12}}$</td>
</tr>
<tr>
<td>$Z_{21}$</td>
<td>$\frac{Z_{21}}{Z_{21}}$</td>
<td>$Z_{21} = \frac{Z_{21}}{Z_{21}}$</td>
</tr>
<tr>
<td>$Z_{22}$</td>
<td>$\frac{Z_{22}}{Z_{22}}$</td>
<td>$Z_{22} = \frac{Z_{22}}{Z_{22}}$</td>
</tr>
</tbody>
</table>
TABLE IV
Equations for the Conversion Between 7 Parameters and Normalized Z, Y, h, and ABCD Parameters with a Source Impedance Z₁₀₁ and Load Impedance Z₀₂

\[ T_{11} = \frac{(a_{11} + 1)[(a_{21} + 1)] - a_{21} a_{21}}{2 a_{21}} \]  
\[ T_{12} = \frac{(a_{11} + 1)[(a_{21} + 1)] - a_{21} a_{21}}{2 a_{21}} \]  
\[ T_{21} = \frac{(a_{11} + 1)[(a_{21} + 1)] - a_{21} a_{21}}{2 a_{21}} \]  
\[ T_{22} = \frac{(a_{11} + 1)[(a_{21} + 1)] - a_{21} a_{21}}{2 a_{21}} \]

\[ Z_{12n} = \frac{2 a_{21} [T_{11} + T_{12} + (T_{21} + T_{22})]}{T_{11} + T_{12} + T_{21} - T_{22}} \]
\[ Z_{12n} = \frac{2 a_{21} [T_{11} + T_{12} + (T_{21} + T_{22})]}{T_{11} + T_{12} + T_{21} - T_{22}} \]
\[ Z_{21n} = \frac{2 a_{21} [T_{11} - T_{21} - (T_{12} + T_{22})]}{T_{11} + T_{12} + T_{21} - T_{22}} \]
\[ Z_{22n} = \frac{2 a_{21} [T_{11} - T_{21} - (T_{12} + T_{22})]}{T_{11} + T_{12} + T_{21} - T_{22}} \]

\[ Z_{11n} = \frac{a_{21}}{a_{21}} \]  
\[ Z_{22n} = \frac{a_{21}}{a_{21}} \]

\[ T_{11} = \frac{-i (1 - \zeta a_h) [a_{11} + a_{22}]^2 + a_{21} a_{21}}{2 a_{21}} \]  
\[ T_{12} = \frac{-i (1 - \zeta a_h) [a_{11} + a_{22}]^2 + a_{21} a_{21}}{2 a_{21}} \]  
\[ T_{21} = \frac{-i (1 - \zeta a_h) [a_{11} + a_{22}]^2 + a_{21} a_{21}}{2 a_{21}} \]  
\[ T_{22} = \frac{-i (1 - \zeta a_h) [a_{11} + a_{22}]^2 + a_{21} a_{21}}{2 a_{21}} \]

\[ Y_{11n} = \frac{T_{11} [T_{11} - T_{21} - (T_{12} + T_{22})]}{T_{11} + T_{12} + T_{21} - T_{22}} \]
\[ Y_{12n} = \frac{T_{11} [T_{11} - T_{21} - (T_{12} + T_{22})]}{T_{11} + T_{12} + T_{21} - T_{22}} \]
\[ Y_{21n} = \frac{T_{11} [T_{11} - T_{21} - (T_{12} + T_{22})]}{T_{11} + T_{12} + T_{21} - T_{22}} \]
\[ Y_{22n} = \frac{T_{11} [T_{11} - T_{21} - (T_{12} + T_{22})]}{T_{11} + T_{12} + T_{21} - T_{22}} \]

\[ h_{11n} = \frac{h_{21}}{h_{21}} \]  
\[ h_{22n} = \frac{h_{21}}{h_{21}} \]

\[ a_{11} = T_{11} + T_{12} + T_{21} + T_{22} \]
\[ a_{22} = T_{11} + T_{12} + T_{21} + T_{22} \]
\[ a_{21} = T_{11} + T_{12} + T_{21} + T_{22} \]
\[ a_{21} = T_{11} + T_{12} + T_{21} + T_{22} \]
between $T$ parameters and $Z$, $Y$, $h$, and $ABCD$ parameters. Tables III and IV provide the conversions from $S$ and $T$ parameters to the normalized $Z$, $Y$, $h$, and $ABCD$ parameters, respectively. From Tables III and IV, it is easy to see that if $Z_{01}$ and $Z_{02}$ are real, the conversions become those shown in many of the references cited, e.g., [21], [41], [17], [18], [11], [12], [14], [15]. Finally, Table V shows the conversions between $Z$, $Y$, $h$, and $ABCD$ parameters while Table VI shows the conversions between $S$ and $T$ parameters. These are included to make the table of conversions in this paper complete.

### IV. VERIFICATION

Using PSPICE, a SPICE based circuit analysis program, a lumped element model of an NE32000 HEMT was analyzed. The netlist was taken from the NEC databook and is shown below:

```
g1 5 6 3 4 0.045
g2 1 2 0.1nh
g3 2 3 2
cgs 3 4 0.2pf
cgd 3 5 0.016pf
cdg 5 4 6.7ff
ri 4 6 4
rs 6 7 3.5
ls 7 10 0.03nh
rds 5 6 200
cds 5 6 7.2ff
rd 5 8 4
ld 8 9 0.09nh.
```

By properly configuring a source at first port 1 then port 2, and opening and shorting out the other port, PSPICE will provide the complex voltages and currents required to calculate the $Z$, $Y$, $h$, and $ABCD$ parameters. Tables VII and VIII show the voltages and currents from PSPICE under the conditions listed in those tables. The $Z$, $Y$, $h$, and $ABCD$ parameters are calculated from these using (1)-(4) and are shown in Table IX.

The NE32000 lumped element model was also analyzed using Super Compact. For no particular reason, I chose to calculate the $S$ parameters for the NE32000 in a system with a source impedance, $Z_01 = 70 + j30$ and load impedance, $Z_02 = 25 - j35$ at the single frequency of 10 GHz. The results of the Super Compact analysis are shown in Table X.

If a person uses the $Z$, $Y$, $h$, or $ABCD$ parameters of Table IX, in the equations of Table I, with $Z_{01} = 70 + j30$ and $Z_{02} = 25 - j35$, they will find that the calculated $S$ parameters agree with those from Super Compact. In a like fashion, using the $S$ parameters of Super Compact in the other equations in Table I will result in $Z$, $Y$, $h$, and $ABCD$ parameters shown in Table IX.

### V. CONCLUSION

This paper developed the equations for converting between the various common 2-port parameters, $Z$, $Y$, $h$, $ABCD$, $S$, and $T$. The equations are derived from the definitions of the various 2-port parameters, the definition of $a_j$ and $b_j$, and basic transmission line theory. As a result, the equations are completely general and are valid for complex and unique source and load impedances.

The validity of these results is shown by first calculating $S$ parameters from $Z$, $Y$, $h$, and $ABCD$ parameters for an NE32000 HEMT in a system with $Z_{01} = 70 + j30$ and $Z_{02} = 25 - j35$. These results agreed with the $S$ parameters produced by Super Compact. Also, beginning with the $S$ parameters from Super Compact, the $Z$, $Y$, $h$, and $ABCD$ parameters are calculated using the equations developed. The results are the same as those calculated from the voltages and currents produced by PSPICE.
TABLE VII

| VOLTAGES AND CURRENTS FOR THE NE32000 HEMT AT 10 GHz with the SOURCE at Port 1. The VOLTAGES AND CURRENTS ARE Defined in Fig. 1. |
|---|---|---|---|
| $I_1$ (Port 2 Open Circulated) | $V_1$ | $V_2$ (Port 2 Short Circulated) |
| $I_2$ | $I_2$ |
| 8.84E-03 + j2.371E-02 | -8.181E+00 + j5.615E+00 | 2.010E-03 + j1.292E-02 | 4.018E-02 - j1.071E-02 |

TABLE VIII

| VOLTAGES AND CURRENTS FOR THE NE32000 HEMT AT 10 GHz with the SOURCE at Port 2. The VOLTAGES AND CURRENTS ARE Defined in Fig. 1. |
|---|---|---|---|
| $I_1$ (Port 1 Open Circulated) | $V_1$ | $V_2$ (Port 1 Short Circulated) |
| $I_2$ | $I_2$ |
| 8.032E-03 + j1.119E-03 | 9.661E-02 + j1.869E-02 | 3.949E-03 + j1.402E-03 | 4.741E-05 - j1.286E-03 |

TABLE IX

| ABCD PARAMETERS FOR THE NE32000 HEMT AT 10 GHz. THESE PARAMETERS WERE CALCULATED FROM THE VOLTAGES AND CURRENTS IN TABLES VII AND VIII USING (1)-(4) |
|---|---|---|---|---|---|
| $Z$ | $Y$ | $h$ | $D$ |
| 1.386E+01 - j3.702E+01 | 2.010E-03 + j1.292E-02 | 1.176E+01 - j7.537E+01 | -8.309E-02 - j5.703E-02 |
| 1.221E-02 - j1.701E+01 | 3.949E-03 + j1.402E-03 | 4.741E-05 - j1.286E-03 |

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REFERENCES


Dean A. Frickey (S’76-M’82) was born in Sheridan, WY on March 10, 1958. He received the B.S. and M.S. degrees in electrical engineering from the South Dakota School of Mines and Technology, Rapid City in 1980 and 1981, respectively. He is pursuing, part-time, the Ph.D. degree in electrical engineering through the University of Idaho, Moscow. He spent one year with the Boeing Military Airplane Company, Seattle, WA, in a systems analysis group before becoming involved in microwave technology at Raytheon Missile Systems Division, Tewksbury, MA, where he spent 6 years mostly involved in the analysis and design of hybrid microwave integrated circuits, but with some time spent working with W-band IMPATT diodes. In November 1989, he joined EG&G Idaho, which operates the Idaho National Engineering Laboratory. His research interests are in microwave theory and applications.