











11:  $t_{\max} = t_{\text{right}}$   
 12: **else**  
 13:  $t_{\min} = t_{\text{left}}$   
 14:  $t_{\max} = t_{\text{right}}$   
 15: **end**  
 16:  $len = t_{\max} - t_{\min}$   
 17: **end**  
 18:  $t_1 = (t_{\max} + t_{\min}) / 2$   
 19: take  $t = t_1$  into (16) to find out  $\mathbf{w}^*$ .  
 20: calculate  $C_S(\mathbf{w}^*) = \max\{\log(s_E^2 R_1(t_1) / s_D^2) / 2, 0\}$ .  
 21: **end**.  
 22: **output:**  $\mathbf{w}^*, C_S(\mathbf{w}^*)$ .

#### IV. ZF CONSTRAINT BASED SIMPLIFICATION

As discussed above, maximizing  $C_S(\mathbf{w})$  under individual power constraint is a complicate problem. In this section, we simplify the problem using a zero-forcing (ZF) constraint on the receiving signal at the eavesdropper, which is equivalent to asking  $\mathbf{w}^H R_g \mathbf{w} = 0$ . It is clear from (5) that the optimal  $\mathbf{w}$  under ZF constraint is given by

$$\begin{aligned}
 & \underset{\mathbf{w}}{\text{maximize:}} \quad \mathbf{w}^H R_h \mathbf{w} \\
 & \text{subject to:} \quad \mathbf{w}^H R_g \mathbf{w} = 0 \\
 & \quad |w_i|^2 \leq p_i, \quad i = 0, \dots, N-1
 \end{aligned} \quad (32)$$

From the analysis similar to that in Theorem 2, we have (32)'s optimal solution can be got through solving the convex problem

$$\begin{aligned}
 & \underset{\mathbf{w}}{\text{maximize:}} \quad \text{Re}(\mathbf{w}^H \mathbf{h}) \\
 & \text{subject to:} \quad \mathbf{w}^H \mathbf{g} = 0 \\
 & \quad |w_i|^2 \leq p_i, \quad i = 0, \dots, N-1
 \end{aligned} \quad (33)$$

Then the maximum secrecy rate under ZF constraint can be written as

$$\max\left\{\frac{1}{2} \log\left(1 + \frac{(\mathbf{w}_z^*)^H R_h(\mathbf{w}_z^*)}{s_D^2}\right), 0\right\} \quad (34)$$

where  $\mathbf{w}_z^*$  is an optimal solution of (33). Note that this value is just sub-optimal, because of the existence of the ZF constraint.

#### V. EXTENSION TO MULTI-ANTENNA CASE

In this section, we will study a more complex scenario as an extension. In this scenario, relay nodes are equipped with multiple omni-directional antennas and other conditions are still the same as those in the former scenario. So in stage I, when the symbol  $X_S$  is transmitted, the received signal  $y_{R,i}$  at  $R_i$  is

$$y_{R,i} = \sum_{j=0}^{N_i-1} x_S l_{i,j} + n_{R,i} \quad (35)$$

where  $l_{i,j}$  means the channel between the source and  $R_i$ 's  $j$ th antenna,  $N_i$  means the number of  $R_i$ 's antenna,  $n_{R,i}$  is the noise at  $R_i$  with variance  $s_{R,i}^2$ .

In stage II, when symbol  $X_S$  is transmitted, the received signal  $y_D$  at  $D$  equals

$$y_D = \sum_{i=0}^{N-1} \sum_{j=0}^{N_i-1} w_{i,j} h_{i,j} X_S + n_D \quad (36)$$

where  $w_{i,j}$  ( $i = 0, 1, \dots, N-1; j = 0, 1, \dots, N_i-1$ ) means the beamforming factor at  $R_i$ 's  $j$ th antenna,  $h_{i,j}$  is the channel between  $R_i$ 's  $j$ th antenna and  $D$ , and  $n_D$  is the noise at  $D$  with variance  $s_D^2$ . The received signal  $y_E$  at  $E$  can be shown as,

$$y_E = \sum_{i=0}^{N-1} \sum_{j=0}^{N_i-1} w_{i,j} g_{i,j} X_S + n_E \quad (37)$$

where  $g_{i,j}$  is the channel between  $R_i$ 's  $j$ th antenna and  $E$ . Define  $\mathbf{w}_i = [w_{i,0}, \dots, w_{i,N_i-1}]^T$ ,  $\mathbf{w} = [\mathbf{w}_0^T, \dots, \mathbf{w}_{N-1}^T]^T$ ,  $\mathbf{h}_i = [h_{i,0}, \dots, h_{i,N_i-1}]^T$ ,  $\mathbf{h} = [\mathbf{h}_0^T, \dots, \mathbf{h}_{N-1}^T]^T$ ,  $\mathbf{g}_i = [g_{i,0}, \dots, g_{i,N_i-1}]^T$ ,  $\mathbf{g} = [\mathbf{g}_0^T, \dots, \mathbf{g}_{N-1}^T]^T$  and  $R_h = \mathbf{h}\mathbf{h}^H$ ,  $R_g = \mathbf{g}\mathbf{g}^H$ . Then we can still express the SNR at  $D$  and  $E$  as  $G_D = |\mathbf{h}^H \mathbf{w}|^2 / s_D^2$  and  $G_E = |\mathbf{g}^H \mathbf{w}|^2 / s_E^2$  respectively. So the secrecy capacity for a given  $\mathbf{w}$  can still be shown as (4).

In order to get the maximum achievable secrecy rate, in this section, the core optimization problem becomes

$$\begin{aligned}
 & \underset{\mathbf{w}}{\text{maximize:}} \quad \frac{s_D^2 + \mathbf{w}^H R_h \mathbf{w}}{s_E^2 + \mathbf{w}^H R_g \mathbf{w}} \\
 & \text{subject to:} \quad |w_i|^2 \leq p_i, \quad i = 0, \dots, N-1
 \end{aligned} \quad (38)$$

Here we still obtain a subproblem by fixing the denominator of (38)'s objective function as  $t$  and change the equality constraint of it by substituting " $\leq$ " for " $=$ " to get another optimization problem. And then, we still denote  $f(t)$  and  $f_1(t)$  as the optimal value of the two optimization problem above respectively and define  $\mathbf{w}^*(t)$ ,  $R(t)$ ,  $t^*$ ,  $w_1^*(t)$ ,  $R_1(t)$ ,  $j(t)$ ,  $t_1$  through the same way in section III. It can be seen that in this section we could have theorems similar with those stated in section III. For these theorems, what need to be noted is that (8), (10), (16) should be substituted by their counterpart, i.e. (38), (39), (40) respectively.







