

Basic IIR Digital Filter Structures

- The causal IIR digital filters we are concerned with in this course are characterized by a real rational transfer function of z^{-1} or, equivalently by a constant coefficient difference equation
- From the difference equation representation, it can be seen that the realization of the causal IIR digital filters requires some form of feedback

Basic IIR Digital Filter Structures

- An N -th order IIR digital transfer function is characterized by $2N+1$ unique coefficients, and in general, requires $2N+1$ multipliers and $2N$ two-input adders for implementation
- **Direct form IIR filters:** Filter structures in which the multiplier coefficients are precisely the coefficients of the transfer function

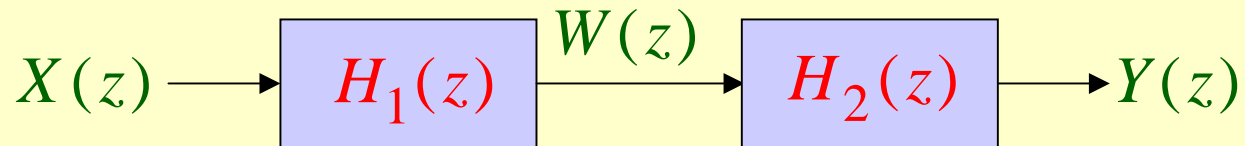
Direct Form IIR Digital Filter Structures

- Consider for simplicity a 3rd-order IIR filter with a transfer function

$$H(z) = \frac{P(z)}{D(z)} = \frac{p_0 + p_1z^{-1} + p_2z^{-2} + p_3z^{-3}}{1 + d_1z^{-1} + d_2z^{-2} + d_3z^{-3}}$$

- We can implement $H(z)$ as a cascade of two filter sections as shown on the next slide

Direct Form IIR Digital Filter Structures



where

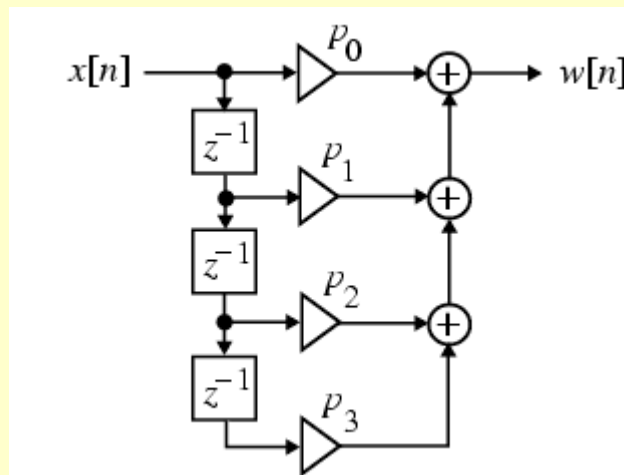
$$H_1(z) = \frac{W(z)}{X(z)} = P(z) = p_0 + p_1z^{-1} + p_2z^{-2} + p_3z^{-3}$$

$$H_2(z) = \frac{Y(z)}{W(z)} = \frac{1}{D(z)} = \frac{1}{1 + d_1z^{-1} + d_2z^{-2} + d_3z^{-3}}$$

Direct Form IIR Digital Filter Structures

- The filter section $H_1(z)$ can be seen to be an FIR filter and can be realized as shown below

$$w[n] = p_0x[n] + p_1x[n-1] + p_2x[n-2] + p_3x[n-3]$$

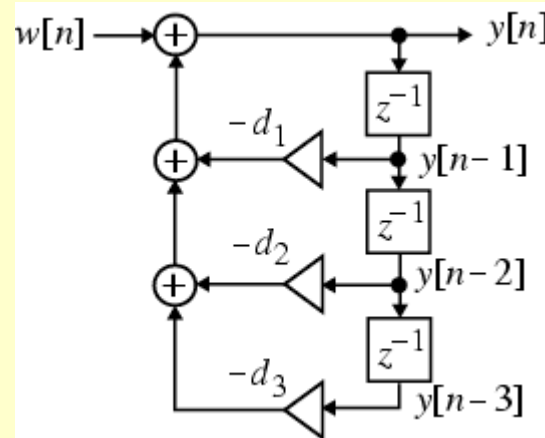


Direct Form IIR Digital Filter Structures

- The time-domain representation of $H_2(z)$ is given by

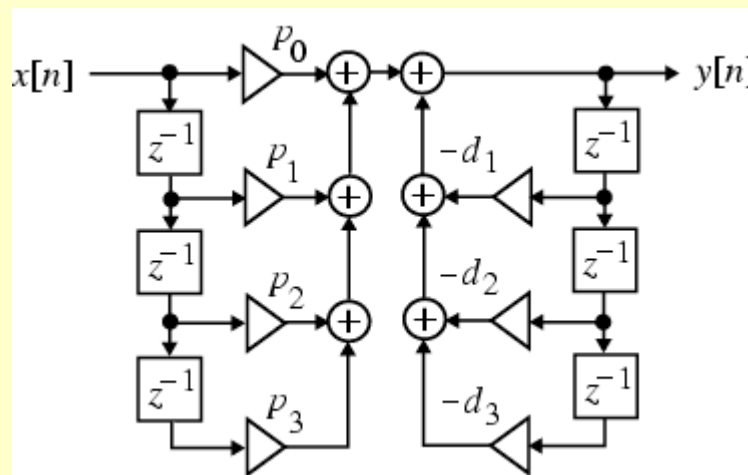
$$y[n] = w[n] - d_1 y[n-1] - d_2 y[n-2] - d_3 y[n-3]$$

Realization of $H_2(z)$ follows from the above equation and is shown on the right



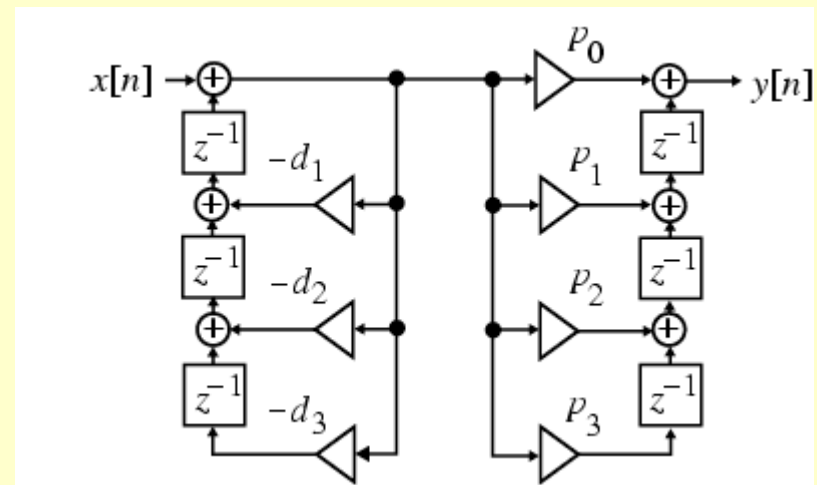
Direct Form IIR Digital Filter Structures

- A cascade of the two structures realizing $H_1(z)$ and $H_2(z)$ leads to the realization of $H(z)$ shown below and is known as the **direct form I** structure



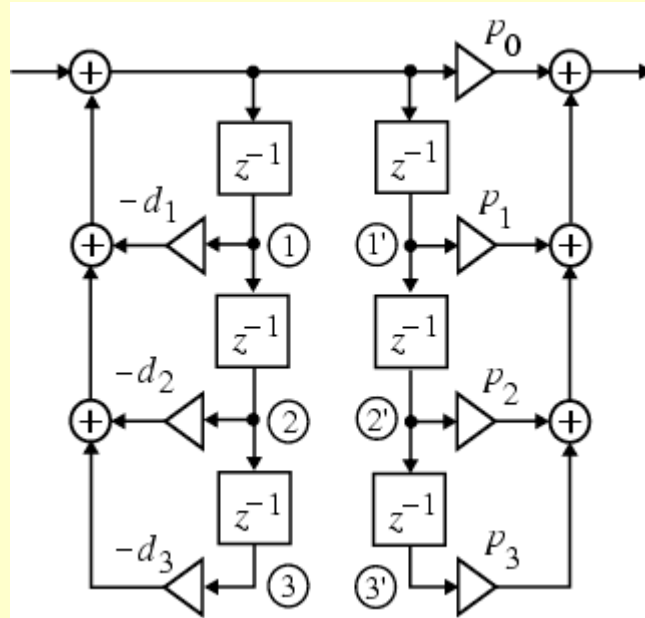
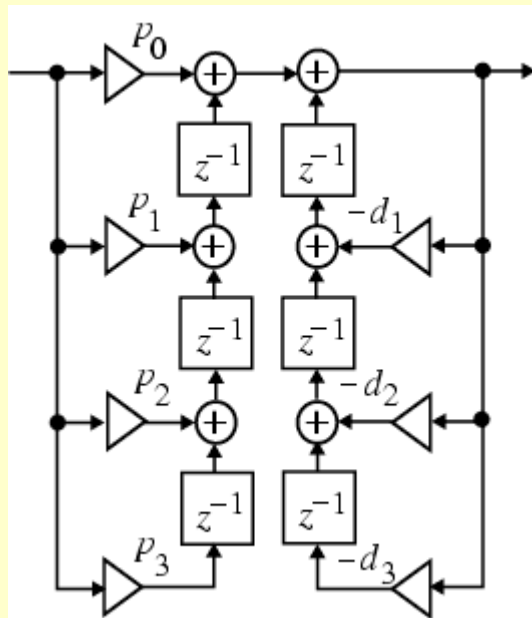
Direct Form IIR Digital Filter Structures

- Note: The direct form I structure is noncanonic as it employs 6 delays to realize a 3rd-order transfer function
- A transpose of the direct form I structure is shown on the right and is called the **direct form I_t** structure



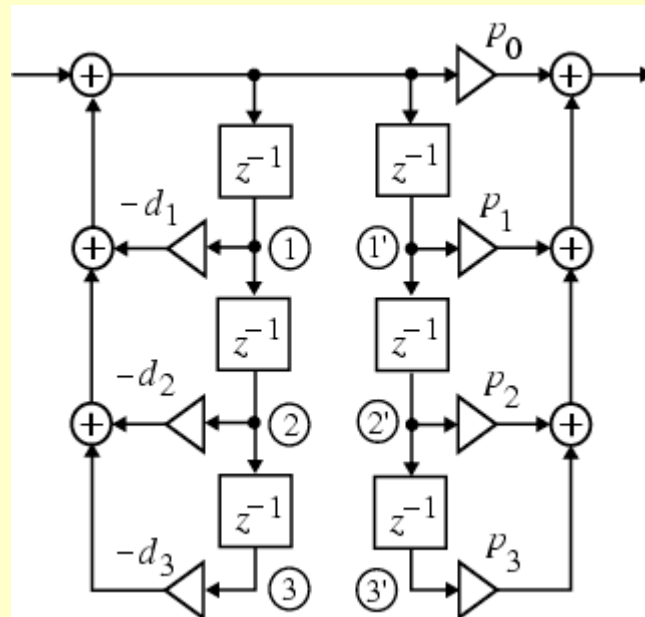
Direct Form IIR Digital Filter Structures

- Various other noncanonic direct form structures can be derived by simple block diagram manipulations as shown below



Direct Form IIR Digital Filter Structures

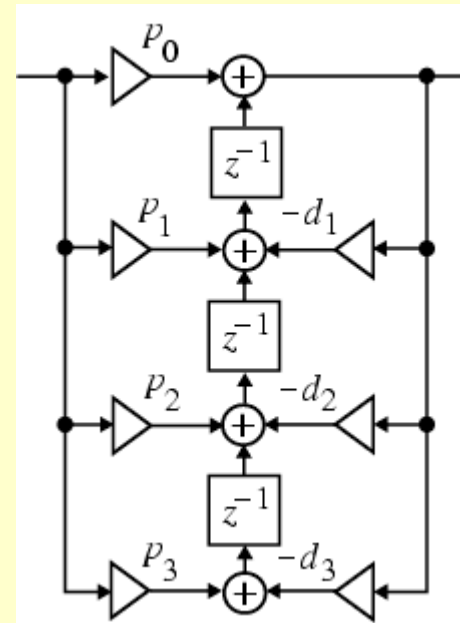
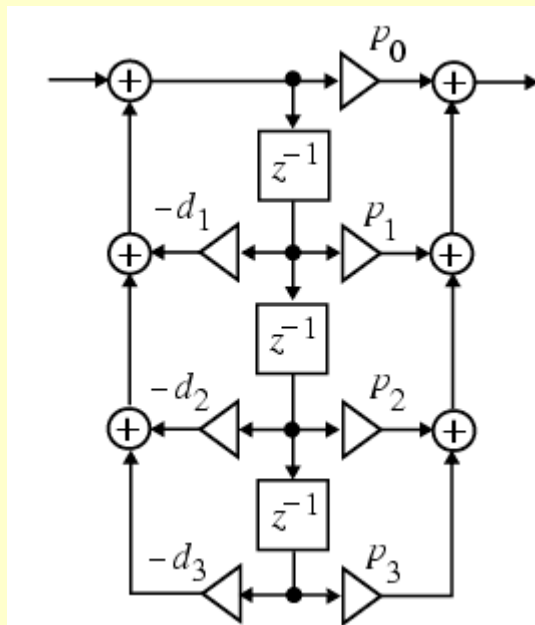
- Observe in the direct form structure shown below, the signal variable at nodes ① and ①' are the same, and hence the two top delays can be shared



Direct Form IIR Digital Filter Structures

- Likewise, the signal variables at nodes ② and ②' are the same, permitting the sharing of the middle two delays
- Following the same argument, the bottom two delays can be shared
- Sharing of all delays reduces the total number of delays to 3 resulting in a canonic realization shown on the next slide along with its transpose structure

Direct Form IIR Digital Filter Structures



- Direct form realizations of an N -th order IIR transfer function should be evident

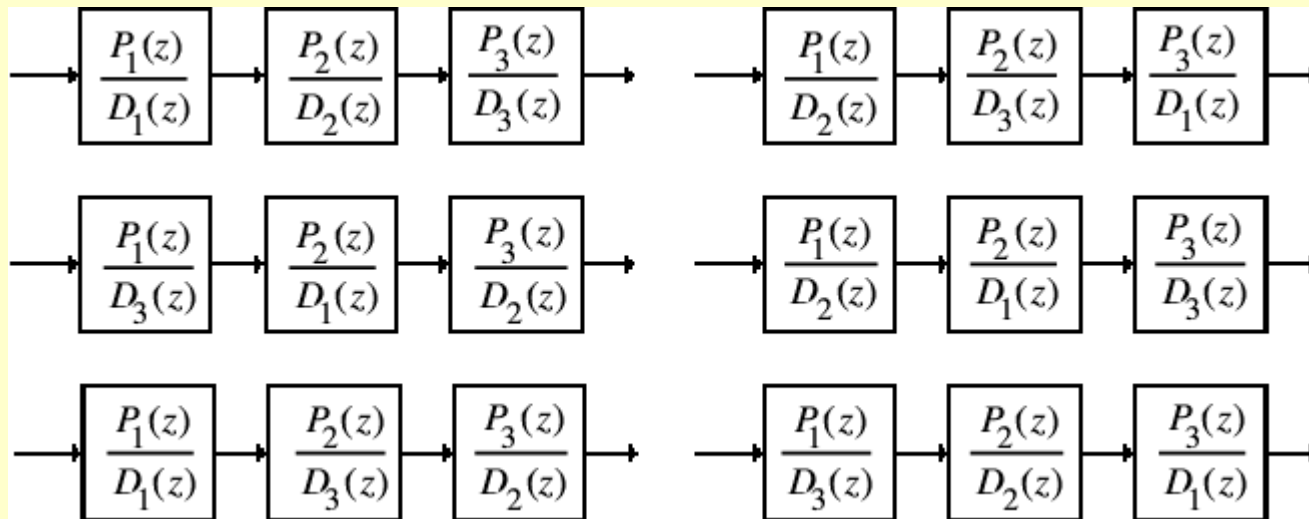
Cascade Form IIR Digital Filter Structures

- By expressing the numerator and the denominator polynomials of the transfer function as a product of polynomials of lower degree, a digital filter can be realized as a cascade of low-order filter sections
- Consider, for example, $H(z) = P(z)/D(z)$ expressed as

$$H(z) = \frac{P(z)}{D(z)} = \frac{P_1(z)P_2(z)P_3(z)}{D_1(z)D_2(z)D_3(z)}$$

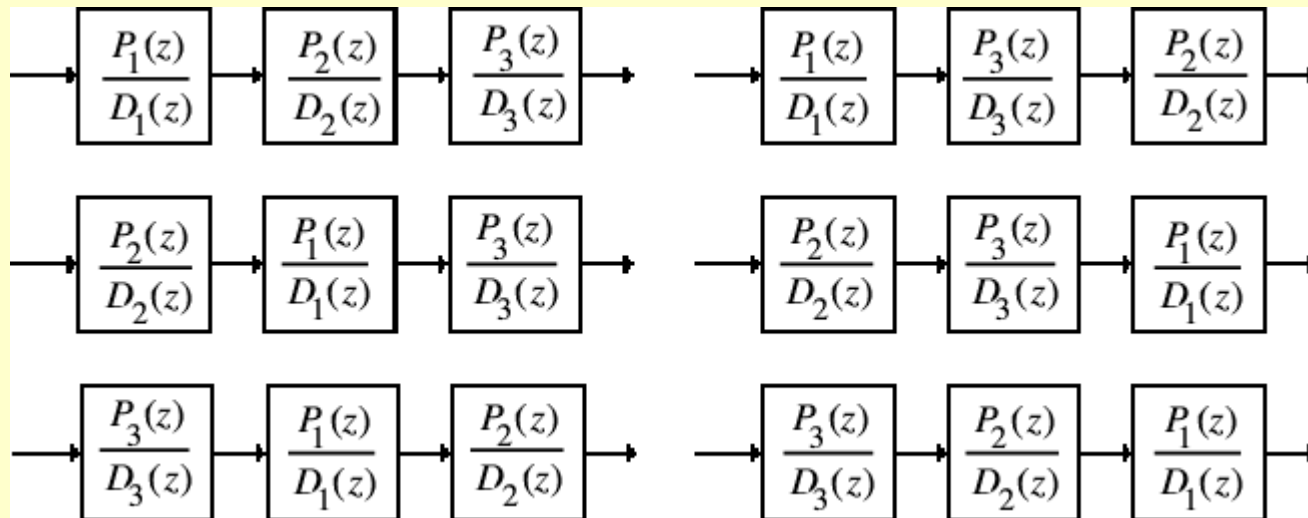
Cascade Form IIR Digital Filter Structures

- Examples of cascade realizations obtained by different pole-zero pairings are shown below



Cascade Form IIR Digital Filter Structures

- Examples of cascade realizations obtained by different ordering of sections are shown below



Cascade Form IIR Digital Filter Structures

- There are altogether a total of 36 different cascade realizations of

$$H(z) = \frac{P_1(z)P_2(z)P_2(z)}{D_1(z)D_2(z)D_3(z)}$$

based on pole-zero-pairings and ordering

- Due to finite wordlength effects, each such cascade realization behaves differently from others

Cascade Form IIR Digital Filter Structures

- Usually, the polynomials are factored into a product of 1st-order and 2nd-order polynomials:

$$H(z) = p_0 \prod_k \left(\frac{1 + \beta_{1k} z^{-1} + \beta_{2k} z^{-2}}{1 + \alpha_{1k} z^{-1} + \alpha_{2k} z^{-2}} \right)$$

- In the above, for a first-order factor

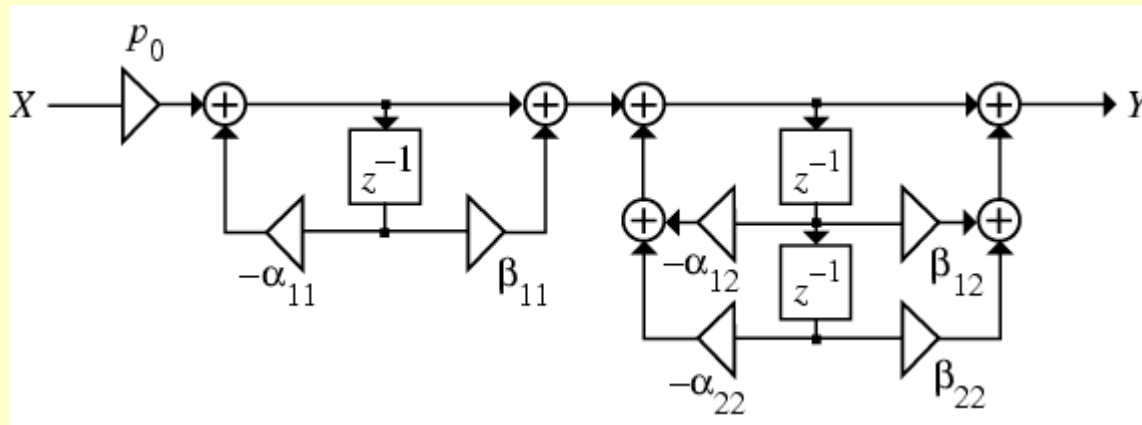
$$\alpha_{2k} = \beta_{2k} = 0$$

Cascade Form IIR Digital Filter Structures

- Consider the 3rd-order transfer function

$$H(z) = p_0 \left(\frac{1 + \beta_{11}z^{-1}}{1 + \alpha_{11}z^{-1}} \right) \left(\frac{1 + \beta_{12}z^{-1} + \beta_{22}z^{-2}}{1 + \alpha_{12}z^{-1} + \alpha_{22}z^{-2}} \right)$$

- One possible realization is shown below



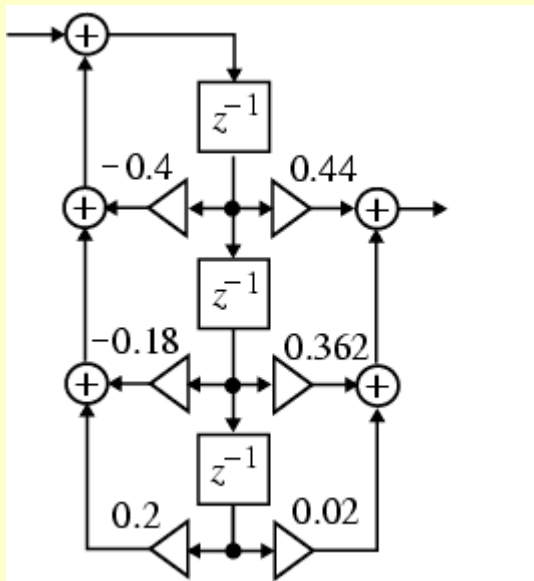
Cascade Form IIR Digital Filter Structures

- Example - Direct form II and cascade form realizations of

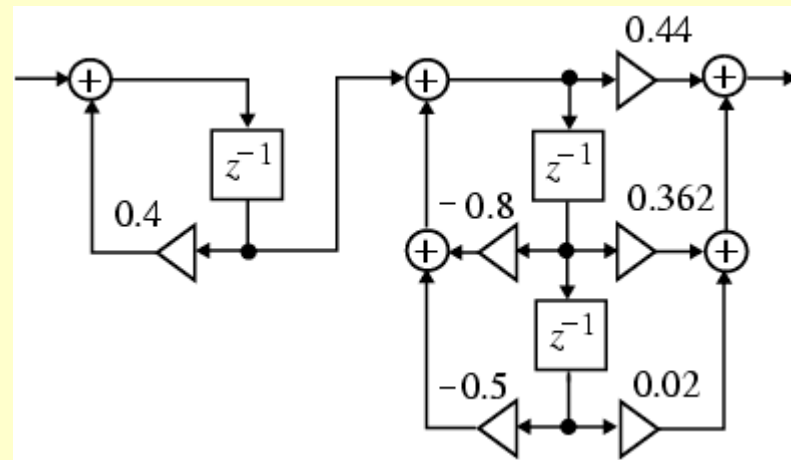
$$H(z) = \frac{0.44z^{-1} + 0.362z^{-2} + 0.02z^{-3}}{1 + 0.4z^{-1} + 0.18z^{-2} - 0.2z^{-3}}$$
$$= \left(\frac{0.44 + 0.362z^{-1} + 0.02z^{-2}}{1 + 0.8z^{-1} + 0.5z^{-2}} \right) \left(\frac{z^{-1}}{1 - 0.4z^{-1}} \right)$$

are shown on the next slide

Cascade Form IIR Digital Filter Structures



Direct form II



Cascade form

Parallel Form IIR Digital Filter Structures

- A partial-fraction expansion of the transfer function in z^{-1} leads to the **parallel form I** structure
- Assuming simple poles, the transfer function $H(z)$ can be expressed as

$$H(z) = \gamma_0 + \sum_k \left(\frac{\gamma_{0k} + \gamma_{1k}z^{-1}}{1 + \alpha_{1k}z^{-1} + \alpha_{2k}z^{-2}} \right)$$

- In the above for a real pole $\alpha_{2k} = \gamma_{1k} = 0$

Parallel Form IIR Digital Filter Structures

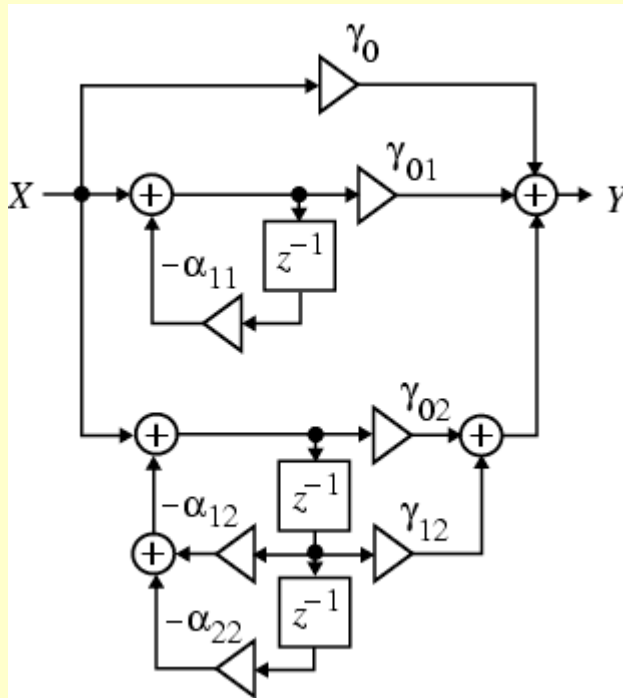
- A direct partial-fraction expansion of the transfer function in z leads to the **parallel form II** structure
- Assuming simple poles, the transfer function $H(z)$ can be expressed as

$$H(z) = \delta_0 + \sum_k \left(\frac{\delta_{0k} z^{-1} + \delta_{2k} z^{-2}}{1 + \alpha_{1k} z^{-1} + \alpha_{2k} z^{-2}} \right)$$

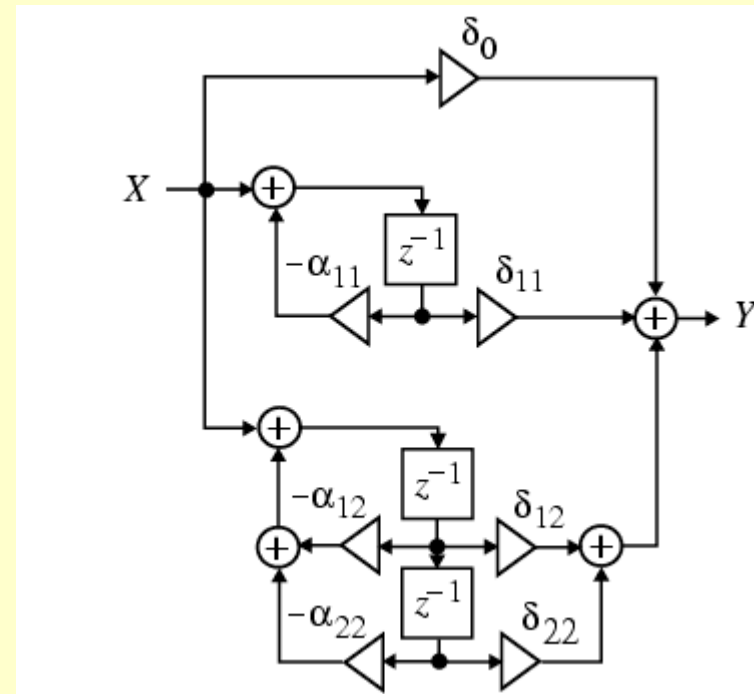
- In the above for a real pole $\alpha_{2k} = \delta_{2k} = 0$

Parallel Form IIR Digital Filter Structures

- The two basic parallel realizations of a 3rd-order IIR transfer function are shown below



Parallel form I



Parallel form II

Parallel Form IIR Digital Filter Structures

- Example - A partial-fraction expansion of

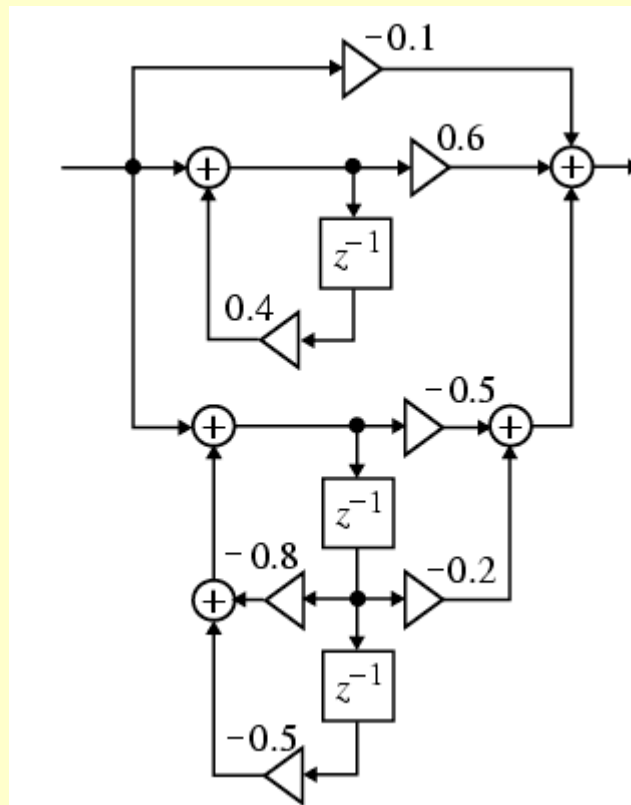
$$H(z) = \frac{0.44z^{-1} + 0.362z^{-2} + 0.02z^{-3}}{1 + 0.4z^{-1} + 0.18z^{-2} - 0.2z^{-3}}$$

in z^{-1} yields

$$H(z) = -0.1 + \frac{0.6}{1 - 0.4z^{-1}} + \frac{-0.5 - 0.2z^{-1}}{1 + 0.8z^{-1} + 0.5z^{-2}}$$

Parallel Form IIR Digital Filter Structures

- The corresponding parallel form I realization is shown below

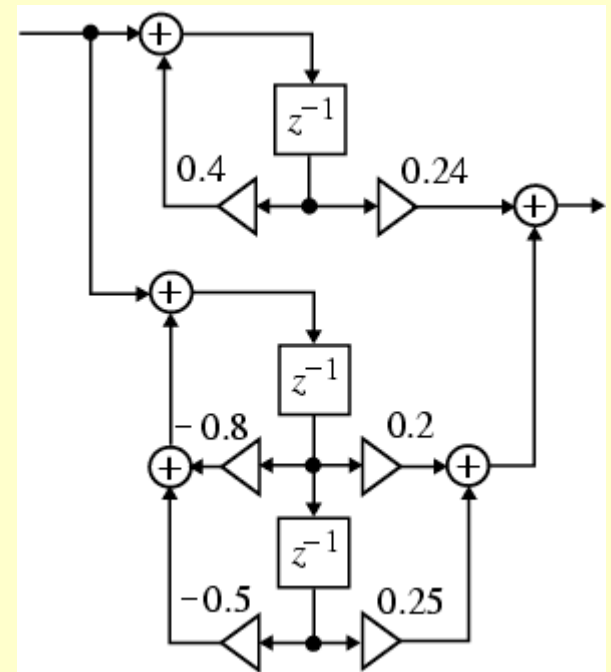


Parallel Form IIR Digital Filter Structures

- Likewise, a partial-fraction expansion of $H(z)$ in z yields

$$H(z) = \frac{0.24z^{-1}}{1-0.4z^{-1}} + \frac{0.2z^{-1} + 0.25z^{-1}}{1+0.8z^{-1} + 0.5z^{-2}}$$

- The corresponding parallel form II realization is shown on the right



Realization Using MATLAB

- The cascade form requires the factorization of the transfer function which can be developed using the M-file `zp2sos`
- The statement `sos = zp2sos(z, p, k)` generates a matrix `sos` containing the coefficients of each 2nd-order section of the equivalent transfer function $H(z)$ determined from its pole-zero form

Realization Using MATLAB

- `sos` is an $L \times 6$ matrix of the form

$$\text{sos} = \begin{bmatrix} p_{01} & p_{11} & p_{21} & d_{01} & d_{11} & d_{21} \\ p_{02} & p_{12} & p_{22} & d_{02} & d_{12} & d_{22} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ p_{0L} & p_{1L} & p_{2L} & d_{0L} & d_{1L} & d_{2L} \end{bmatrix}$$

whose i -th row contains the coefficients $\{p_{il}\}$ and $\{d_{il}\}$, of the the numerator and denominator polynomials of the i -th 2nd-order section

Realization Using MATLAB

- L denotes the number of sections
- The form of the overall transfer function is given by

$$H(z) = \prod_{i=1}^L H_i(z) = \prod_{i=1}^L \frac{p_{0i} + p_{1i}z^{-1} + p_{2i}z^{-2}}{d_{0i} + d_{1i}z^{-1} + d_{2i}z^{-2}}$$

- Program 6_1 can be used to factorize an FIR and an IIR transfer function

Realization Using MATLAB

- **Note:** An FIR transfer function can be treated as an IIR transfer function with a constant numerator of unity and a denominator which is the polynomial describing the FIR transfer function

Realization Using MATLAB

- Parallel forms I and II can be developed using the functions `residuez` and `residue`, respectively
- Program 6_2 uses these two functions

Realization of Allpass Filters

- An M -th order real-coefficient allpass transfer function $A_M(z)$ is characterized by M unique coefficients as here the numerator is the mirror-image polynomial of the denominator
- A direct form realization of $A_M(z)$ requires $2M$ multipliers
- Objective - Develop realizations of $A_M(z)$ requiring only M multipliers

Realization Using Multiplier Extraction Approach

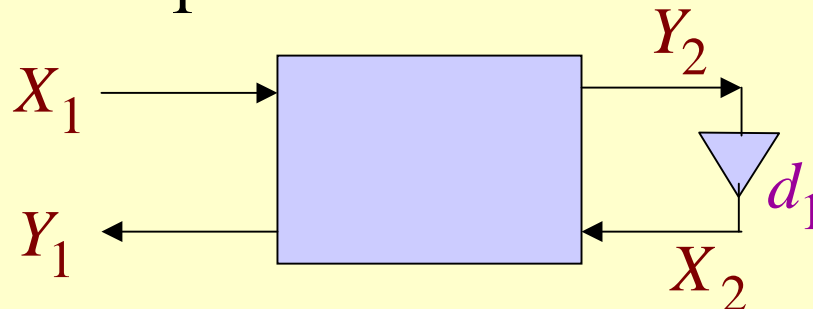
- Now, an arbitrary allpass transfer function can be expressed as a product of 2nd-order and/or 1st-order allpass transfer functions
- We consider first the minimum multiplier realization of a 1st-order and a 2nd-order allpass transfer functions

First-Order Allpass Structures

- Consider first the 1st-order allpass transfer function given by

$$A_1(z) = \frac{d_1 + z^{-1}}{1 + d_1 z^{-1}}$$

- We shall realize the above transfer function in the form a structure containing a single multiplier d_1 as shown below



First-Order Allpass Structures

- We express the transfer function $A_1(z) = Y_1 / X_1$ in terms of the transfer parameters of the two-pair as

$$A_1(z) = t_{11} + \frac{t_{12}t_{21}d_1}{1-d_1t_{22}} = \frac{t_{11} - d_1(t_{11}t_{22} - t_{12}t_{21})}{1-d_1t_{22}}$$

- A comparison of the above with

$$A_1(z) = \frac{d_1 + z^{-1}}{1 + d_1z^{-1}}$$

yields

$$t_{11} = z^{-1}, \quad t_{22} = -z^{-1}, \quad t_{11}t_{22} - t_{12}t_{21} = -1$$

First-Order Allpass Structures

- Substituting $t_{11} = z^{-1}$ and $t_{22} = -z^{-1}$ in $t_{11}t_{22} - t_{12}t_{21} = -1$ we get

$$t_{12}t_{21} = 1 - z^{-2}$$

- There are 4 possible solutions to the above equation:

Type 1A: $t_{11} = z^{-1}$, $t_{22} = -z^{-1}$, $t_{12} = 1 - z^{-2}$, $t_{21} = 1$

Type 1B:

$$t_{11} = z^{-1}, t_{22} = -z^{-1}, t_{12} = 1 + z^{-1}, t_{21} = 1 - z^{-1}$$

First-Order Allpass Structures

- Type 1A_t : $t_{11} = z^{-1}$, $t_{22} = -z^{-1}$, $t_{12} = 1$, $t_{21} = 1 - z^{-2}$
- Type 1B_t :
$$t_{11} = z^{-1}$$
, $t_{22} = -z^{-1}$, $t_{12} = 1 - z^{-1}$, $t_{21} = 1 + z^{-1}$
- We now develop the two-pair structure for the Type 1A allpass transfer function

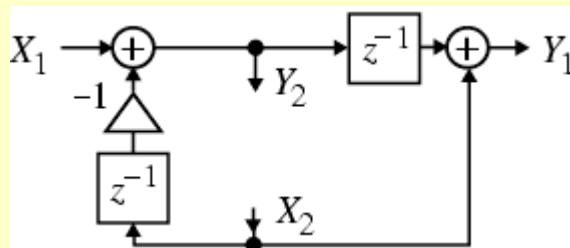
First-Order Allpass Structures

- From the transfer parameters of this allpass we arrive at the input-output relations:

$$Y_2 = X_1 - z^{-1}X_2$$

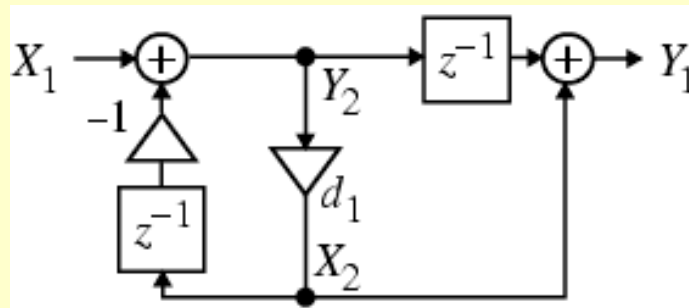
$$Y_1 = z^{-1}X_1 + (1 - z^{-2})X_2 = z^{-1}Y_2 + X_2$$

- A realization of the above two-pair is sketched below



First-Order Allpass Structures

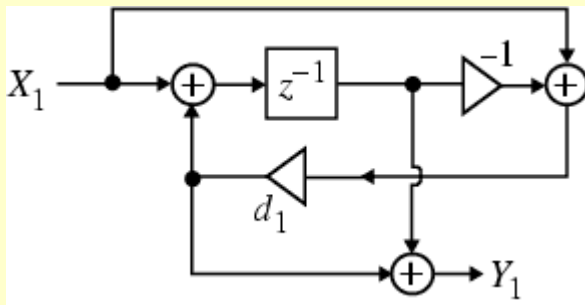
- By constraining the X_2, Y_2 terminal-pair with the multiplier d_1 , we arrive at the Type 1A allpass filter structure shown below



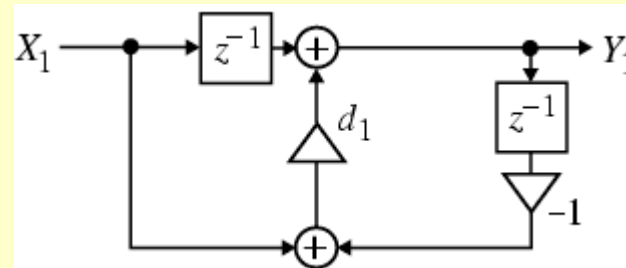
Type 1A

First-Order Allpass Structures

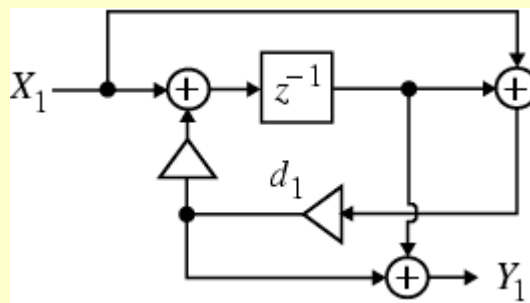
- In a similar fashion, the other three single-multiplier first-order allpass filter structures can be developed as shown below



Type 1B



Type 1A_t



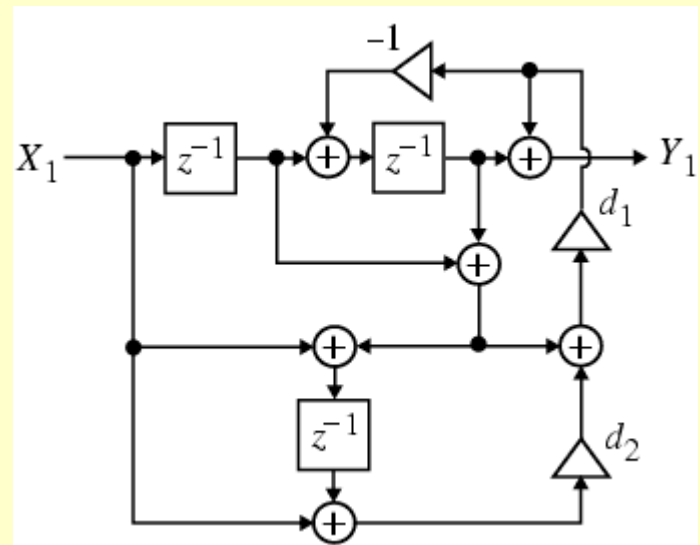
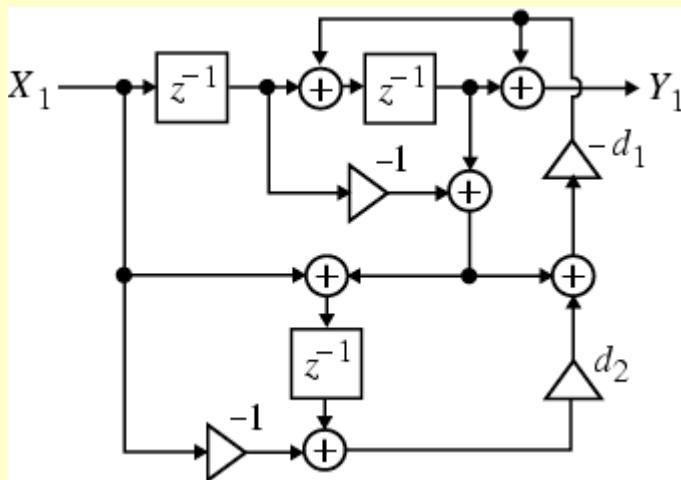
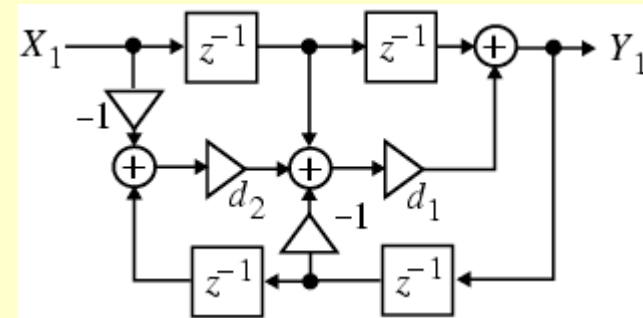
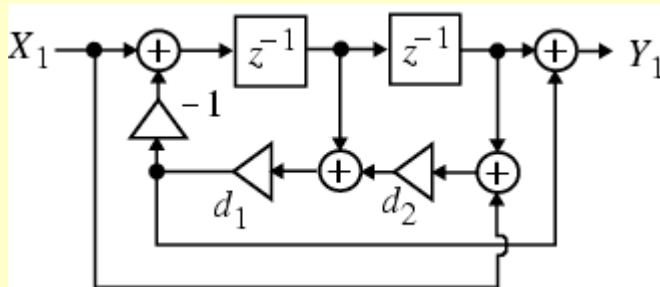
Type 1B_t

Second-Order Allpass Structures

- A 2nd-order allpass transfer function is characterized by 2 unique coefficients
- Hence, it can be realized using only 2 multipliers
- Type 2 allpass transfer function:

$$A_2(z) = \frac{d_1 d_2 + d_1 z^{-1} + z^{-2}}{1 + d_1 z^{-1} + d_1 d_2 z^{-2}}$$

Type 2 Allpass Structures

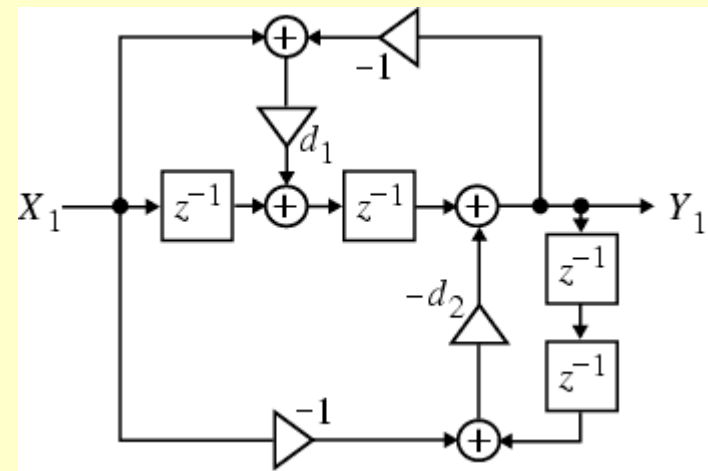
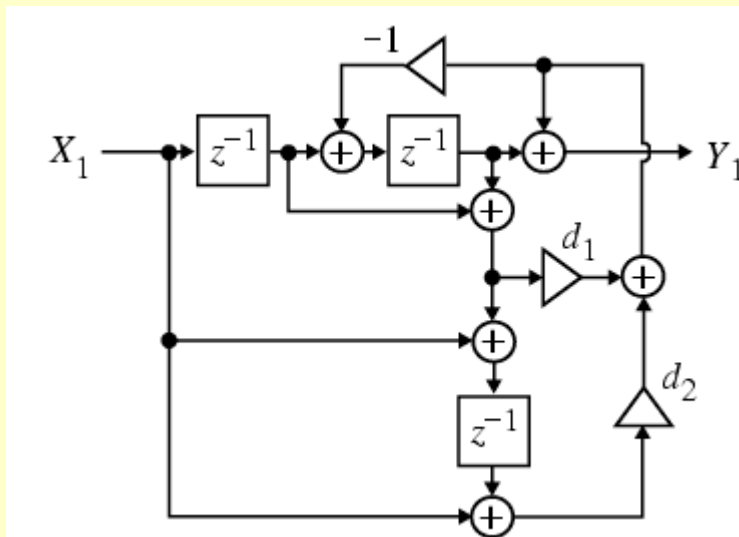
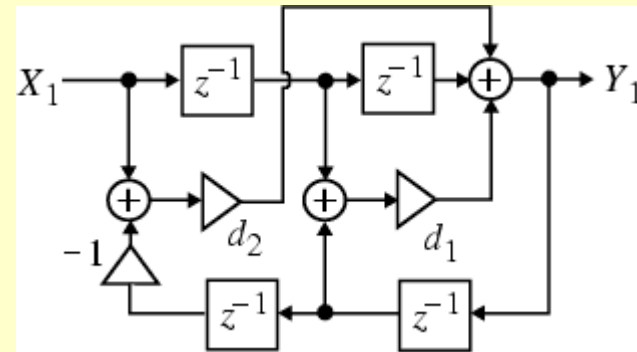
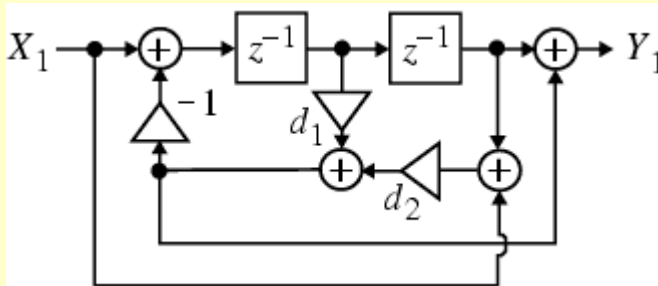


Type 3 Allpass Structures

- Type 3 allpass transfer function:

$$A_3(z) = \frac{d_2 + d_1 z^{-1} + z^{-2}}{1 + d_1 z^{-1} + d_2 z^{-2}}$$

Type 3 Allpass Structures



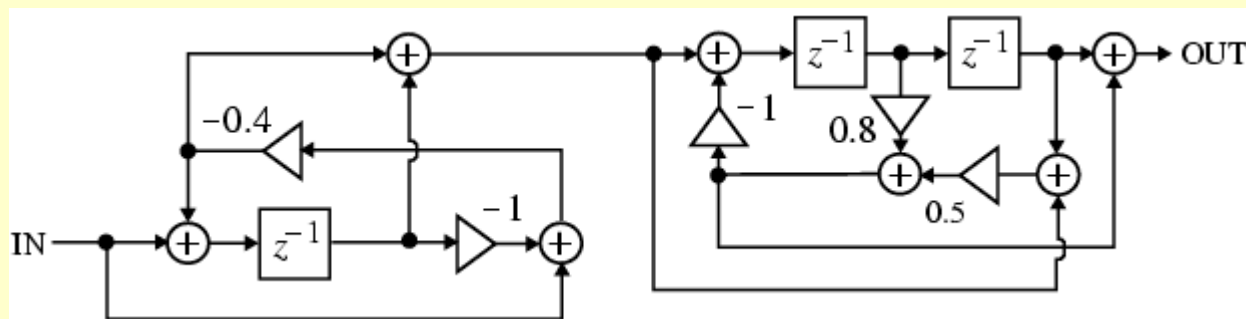
Realization Using Multiplier Extraction Approach

- Example - Realize

$$A_3(z) = \frac{-0.2 + 0.18z^{-1} + 0.4z^{-2} + z^{-3}}{1 + 0.4z^{-1} + 0.18z^{-2} - 0.2z^{-3}}$$

$$= \frac{(-0.4 + z^{-1})(0.5 + 0.8z^{-1} + z^{-2})}{(1 - 0.4z^{-1})(1 + 0.8z^{-1} + 0.5z^{-2})}$$

- A 3-multiplier cascade realization of the above allpass transfer function is shown below



Realization Using Two-Pair Extraction Approach

- The stability test algorithm described earlier in the course also leads to an elegant realization of an M th-order allpass transfer function
- The algorithm is based on the development of a series of $(m-1)$ th-order allpass transfer functions $A_{m-1}(z)$ from an m th-order allpass transfer function $A_m(z)$ for $m = M, M-1, \dots, 1$

Realization Using Two-Pair Extraction Approach

- **Let**

$$A_m(z) = \frac{d_m + d_{m-1}z^{-1} + d_{m-2}z^{-2} + \dots + d_1z^{-(m-1)} + z^{-m}}{1 + d_1z^{-1} + d_2z^{-2} + \dots + d_{m-1}z^{-(m-1)} + d_mz^{-m}}$$

- **We use the recursion**

$$A_{m-1}(z) = z \left[\frac{A_m(z) - k_m}{1 - k_m A_m(z)} \right], \quad m = M, M-1, \dots, 1$$

where $k_m = A_m(\infty) = d_m$

- It has been shown earlier that $A_M(z)$ is stable if and only if

$$k_m^2 < 1 \quad \text{for } m = M, M-1, \dots, 1$$

Realization Using Two-Pair Extraction Approach

- If the allpass transfer function $A_{m-1}(z)$ is expressed in the form

$$A_{m-1}(z) = \frac{d'_{m-1} + d'_{m-2}z^{-1} + \dots + d'_1z^{-(m-2)} + z^{-(m-1)}}{1 + d'_1z^{-1} + \dots + d'_{m-2}z^{-(m-2)} + d'_{m-1}z^{-(m-1)}}$$

then the coefficients of $A_{m-1}(z)$ are simply related to the coefficients of $A_m(z)$ through

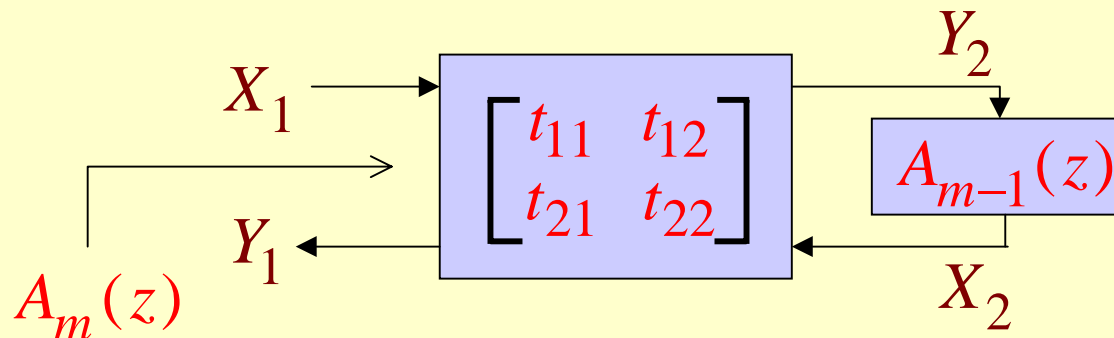
$$d'_i = \frac{d_i - d_m d_{m-i}}{1 - d_m^2}, \quad 1 \leq i \leq m-1$$

Realization Using Two-Pair Extraction Approach

- To develop the realization method we express $A_m(z)$ in terms of $A_{m-1}(z)$:

$$A_m(z) = \frac{k_m + z^{-1} A_{m-1}(z)}{1 + k_m z^{-1} A_{m-1}(z)}$$

- We realize $A_m(z)$ in the form shown below



Realization Using Two-Pair Extraction Approach

- The transfer function $A_m(z) = Y_1/X_1$ of the constrained two-pair can be expressed as

$$A_m(z) = \frac{t_{11} - (t_{11}t_{22} - t_{12}t_{21})A_{m-1}(z)}{1 - t_{22}A_{m-1}(z)}$$

- Comparing the above with

$$A_m(z) = \frac{k_m + z^{-1}A_{m-1}(z)}{1 + k_m z^{-1}A_{m-1}(z)}$$

we arrive at the two-pair transfer parameters

Realization Using Two-Pair Extraction Approach

$$t_{11} = k_m, \quad t_{22} = -k_m z^{-1}$$

$$t_{11}t_{22} - t_{12}t_{21} = -z^{-1}$$

- Substituting $t_{11} = k_m$ and $t_{22} = -k_m z^{-1}$ in the equation above we get

$$t_{12}t_{21} = (1 - k_m^2)z^{-1}$$

- There are a number of solutions for t_{12} and t_{21}

Realization Using Two-Pair Extraction Approach

- Some possible solutions are given below:

$$t_{11} = k_m, t_{22} = -k_m z^{-1}, t_{12} = z^{-1}, t_{21} = 1 - k_m^2$$

$$t_{11} = k_m, t_{22} = -k_m z^{-1}, t_{12} = (1 - k_m) z^{-1}, t_{21} = 1 + k_m$$

$$t_{11} = k_m, t_{22} = -k_m z^{-1}, t_{12} = \sqrt{1 - k_m^2} z^{-1}, t_{21} = \sqrt{1 - k_m^2}$$

$$t_{11} = k_m, t_{22} = -k_m z^{-1}, t_{12} = (1 - k_m^2) z^{-1}, t_{21} = 1$$

Realization Using Two-Pair Extraction Approach

- Consider the solution

$$t_{11} = k_m, \quad t_{22} = -k_m z^{-1}, \quad t_{12} = (1 - k_m^2) z^{-1}, \quad t_{21} = 1$$

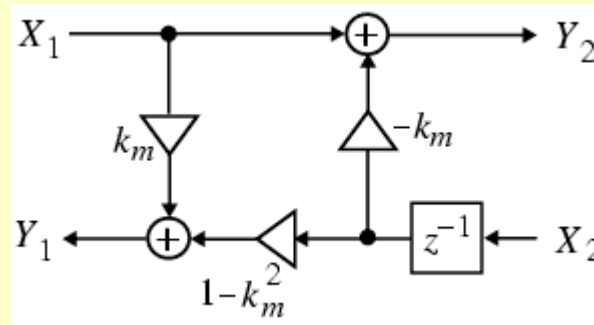
- Corresponding input-output relations are

$$Y_1 = k_m X_1 - (1 - k_m^2) z^{-1} X_2$$

$$Y_2 = X_1 - k_m z^{-1} X_2$$

- A direct realization of the above equations leads to the 3-multiplier two-pair shown on the next slide

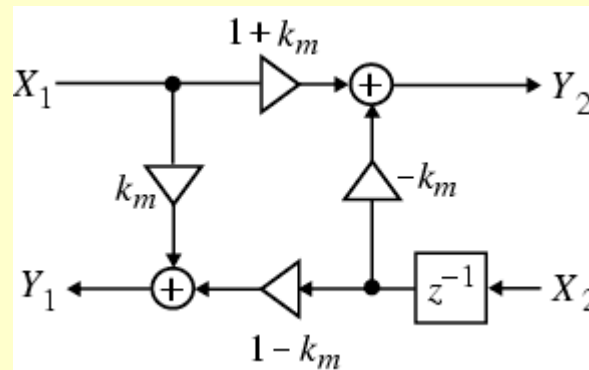
Realization Using Two-Pair Extraction Approach



- The transfer parameters

$$t_{11} = k_m, \quad t_{22} = -k_m z^{-1}, \quad t_{12} = (1 - k_m) z^{-1}, \quad t_{21} = 1 + k_m$$

lead to the 4-multiplier two-pair structure shown below

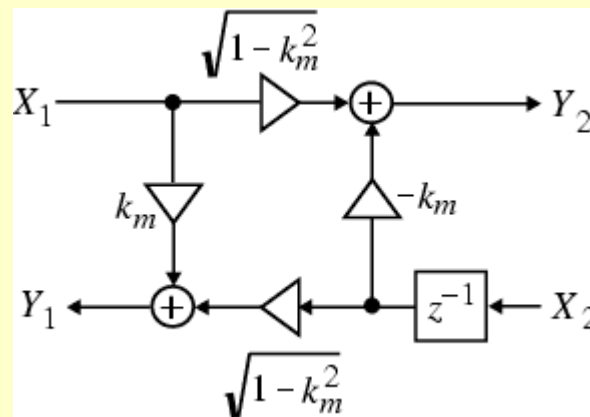


Realization Using Two-Pair Extraction Approach

- Likewise, the transfer parameters

$$t_{11} = k_m, \quad t_{22} = -k_m z^{-1}, \quad t_{12} = \sqrt{1 - k_m^2} z^{-1}, \quad t_{21} = \sqrt{1 - k_m^2}$$

lead to the 4-multiplier two-pair structure shown below



Realization Using Two-Pair Extraction Approach

- A 2-multiplier realization can be derived by manipulating the input-output relations:

$$Y_1 = k_m X_1 - (1 - k_m^2) z^{-1} X_2$$

$$Y_2 = X_1 - k_m z^{-1} X_2$$

- Making use of the second equation, we can rewrite the first equation as

$$Y_1 = k_m Y_2 + z^{-1} X_2$$

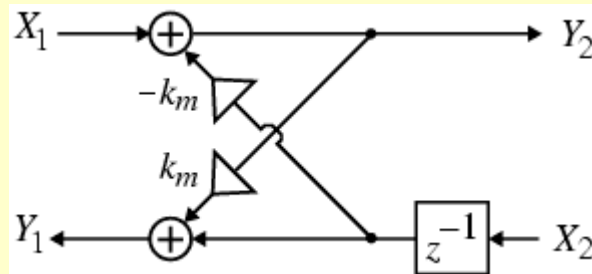
Realization Using Two-Pair Extraction Approach

- A direct realization of

$$Y_1 = k_m Y_2 + z^{-1} X_2$$

$$Y_2 = X_1 - k_m z^{-1} X_2$$

lead to the 2-multiplier two-pair structure, known as the **lattice structure**, shown below



Realization Using Two-Pair Extraction Approach

- Consider the two-pair described by

$$t_{11} = k_m, \quad t_{22} = -k_m z^{-1}, \quad t_{12} = (1 - k_m)z^{-1}, \quad t_{21} = 1 + k_m$$

- Its input-output relations are given by

$$Y_1 = k_m X_1 + (1 - k_m)z^{-1} X_2$$

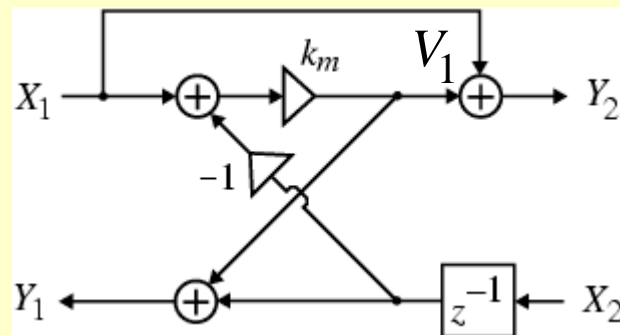
$$Y_2 = (1 + k_m)X_1 - k_m z^{-1} X_2$$

- Define

$$V_1 = k_m (X_1 - z^{-1})X_2$$

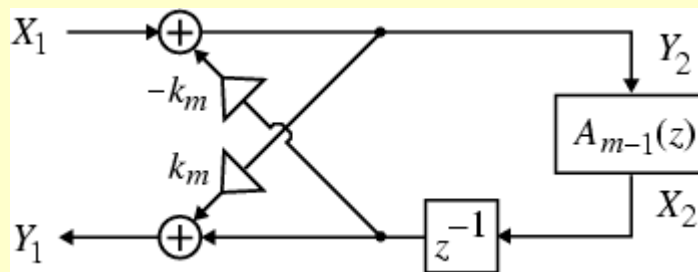
Realization Using Two-Pair Extraction Approach

- We can then rewrite the input-output relations as $Y_1 = V_1 + z^{-1}X_2$ and $Y_2 = X_1 + V_1$
- The corresponding 1-multiplier realization is shown below



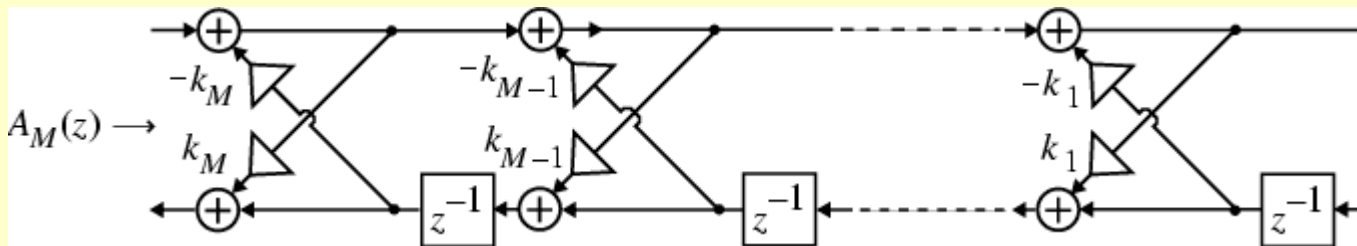
Realization Using Two-Pair Extraction Approach

- An m th-order allpass transfer function $A_m(z)$ is then realized by constraining any one of the two-pairs developed earlier by the $(m-1)$ th-order allpass transfer function $A_{m-1}(z)$



Realization Using Two-Pair Extraction Approach

- The process is repeated until the constraining transfer function is $A_0(z) = 1$
- The complete realization of $A_M(z)$ based on the extraction of the two-pair lattice is shown below



Realization Using Two-Pair Extraction Approach

- It follows from our earlier discussion that $A_M(z)$ is stable if the magnitudes of all multiplier coefficients in the realization are less than 1, i.e., $|k_m| < 1$ for $m = M, M - 1, \dots, 1$
- The cascaded lattice allpass filter structure requires $2M$ multipliers
- A realization with M multipliers is obtained if instead the single multiplier two-pair is used

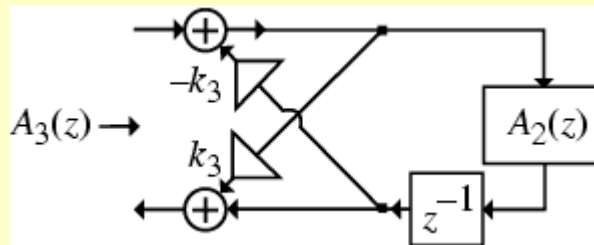
Realization Using Two-Pair Extraction Approach

- Example - Realize

$$\begin{aligned} A_3(z) &= \frac{-0.2 + 0.18z^{-1} + 0.4z^{-2} + z^{-3}}{1 + 0.4z^{-1} + 0.18z^{-2} - 0.2z^{-3}} \\ &= \frac{d_1 + d_2z^{-1} + d_1z^{-2} + z^{-3}}{1 + d_1z^{-1} + d_2z^{-2} + d_3z^{-3}} \end{aligned}$$

Realization Using Two-Pair Extraction Approach

- We first realize $A_3(z)$ in the form of a lattice two-pair characterized by the multiplier coefficient $k_3 = d_3 = -0.2$ and constrained by a 2nd-order allpass $A_2(z)$ as indicated below



$$k_3 = -0.2$$

Realization Using Two-Pair Extraction Approach

- The allpass transfer function $A_2(z)$ is of the form

$$A_2(z) = \frac{d_2' + d_1'z^{-1} + z^{-2}}{1 + d_1'z^{-1} + d_2'z^{-2}}$$

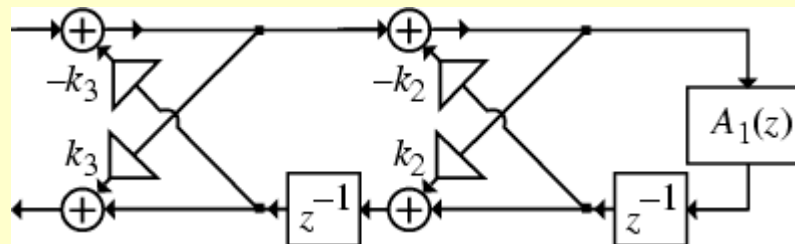
- Its coefficients are given by

$$d_1' = \frac{d_1 - d_3 d_2}{1 - d_3^2} = \frac{0.4 - (-0.2)(0.18)}{1 - (-0.2)^2} = 0.4541667$$

$$d_2' = \frac{d_2 - d_3 d_1}{1 - d_3^2} = \frac{0.18 - (-0.2)(0.4)}{1 - (-0.2)^2} = 0.2708333$$

Realization Using Two-Pair Extraction Approach

- Next, the allpass $A_2(z)$ is realized as a lattice two-pair characterized by the multiplier coefficient $k_2 = d_2' = 0.2708333$ and constrained by an allpass $A_1(z)$ as indicated below



$$k_3 = -0.2, \quad k_2 = 0.2708333$$

Realization Using Two-Pair Extraction Approach

- The allpass transfer function $A_1(z)$ is of the form

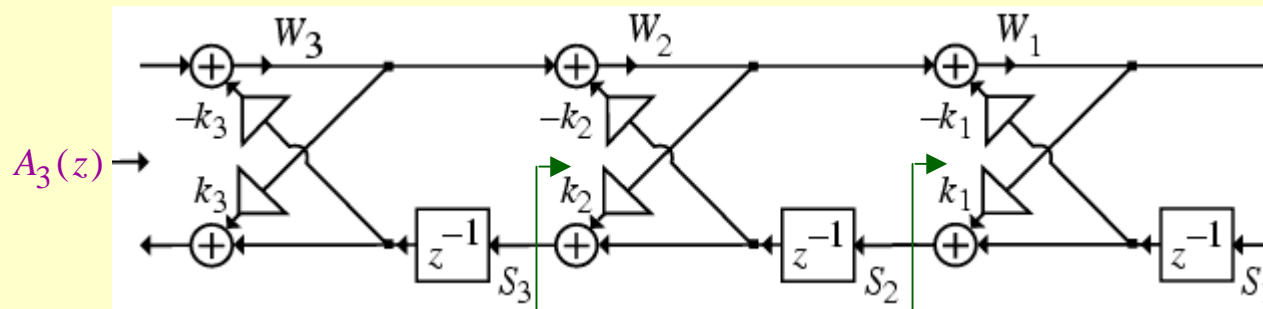
$$A_1(z) = \frac{d_1'' + z^{-1}}{1 + d_1'' z^{-1}}$$

- Its coefficient is given by

$$d_1'' = \frac{d_1' - d_2' d_1'}{1 - (d_2')^2} = \frac{d_1'}{1 + d_2'} = \frac{0.4541667}{1.2708333} = 0.3573771$$

Realization Using Two-Pair Extraction Approach

- Finally, the allpass $A_1(z)$ is realized as a lattice two-pair characterized by the multiplier coefficient $k_1 = d_1'' = 0.3573771$ and constrained by an allpass $A_0(z) = 1$ as indicated below



$$k_3 = -0.2,$$

$$k_2 = 0.2708333, \quad k_1 = 0.3573771$$

Cascaded Lattice Realization Using MATLAB

- The M-file `poly2rc` can be used to realize an allpass transfer function in the cascaded lattice form
- To this end Program 6_3 can be employed