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A NEW APPROACH TO DECENTRALIZED CONTROL DESIGN FOR NONLINEAR MULTI-UNIT PLANTS

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Abstract

In this paper, a new approach is proposed to evaluate a set of plant decompositions in an operating space. This space corresponds to the variation of the operating point caused by disturbances. The proposed method enables the determination of the best local plant decompositions based on a specific performance criterion. Once the best local plant decompositions are obtained, local decentralized controllers can be designed.

1 Introduction

Generally, a decentralized control structure is preferred to a centralized structure in controlling a multi-unit chemical process. A common method of applying the decentralized control strategy is to generate a linearized model of the process and then to design robust controllers based on this model.

Unfortunately, due to the inherent nonlinearity in chemical processes, it is often impossible to design a satisfactory decentralized controller for some particular plant decompositions, due to the interactions between multiple units or subsystems. Hence, it is necessary to analyze possible plant decompositions in order to obtain the best plant decomposition for a known plant operating point. However, existing disturbances will often influence the plant operating point and possibly invalidate the best plant decomposition obtained at a particular operating point.

Samyudia *et al*. [12] have proposed a methodology of measuring the interactions between multiple units at a specific operating point. The method proposed in Samyudia *et al*. [12] was derived by using the gap metric and normalized coprime factorization concepts of robust control theory, and considers both the stability and achievable performance of the system under decentralized control. It is interesting to note that the interaction measure requires only open loop information. Therefore, alternative plant decompositions can be screened before the controllers are designed. Furthermore, the proposed indicators which form the criterion for best decomposition selection are also indicators of the stability and performance of the closed-loop system under decentralized control. Hence if a best plant composition is determined using the proposed method, a decentralized controller can be designed based on this decomposition. By applying the decentralized controller to the nonlinear plant, the resultant closed-loop system has performance close to the closed-loop system under fully centralized control.

This paper further generalizes the methodology proposed in Samyudia *et al*. [12]. Instead of searching for one best plant composition at a specific operating point, this work is aimed at finding the best plant decomposition sub-regions in an overall operating space. It will be shown in the sequence that a given operating space can be divided into several sub-regions with each sub-region admitting the same best plant decomposition structure. Therefore, a unified local decentralized controller can be designed for a sub-region to get good local closed-loop performance. At each specific operating point of the operating region, the method proposed in this paper employs the result in Samyudia *et al*. [12], hence the results in this paper enjoy the same advantages as the results in Samyudia *et al*. [12].

This paper is organized as follows: Section 2 addresses the multi-unit decentralized control design approach. In section 3, the proposed methodology is applied to a reactor/separation process to further illustrate the design procedure. Finally, some conclusions end the paper.

2 Multi-unit Decentralized Control Design

2.1 A gap metric methodology for analysis and design at an operating point

Suppose a linearized model for a multi-unit nonlinear process is defined at an operating point by a transfer function G that maps the vector of manipulated variables u_i to the vector of the controlled variables y_i:

$$\begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} = G \begin{bmatrix} u_1 \\ \vdots \\ u_k \end{bmatrix}. \quad (1)$$

with

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$$G = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1m} \\ G_{21} & G_{22} & \cdots & G_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ G_{m1} & G_{m2} & \cdots & G_{mm} \end{bmatrix},$$

where G_{ii} represents the i-th unit and G_{ij}, G_{ji} represent the interactions between the i-th unit and the j-th unit.

A standard decentralized design is to use the diagonal system G_d as the design model:

$$G_d = \begin{bmatrix} G_{11} & 0 & \cdots & 0 \\ 0 & G_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & G_{mm} \end{bmatrix} \qquad (2)$$

Then a decentralized controller K_d can be synthesized based on the design model G_d and applied to the original system G.

However, this standard decentralized design neglects all of the interactions between units. As a consequence, this design may result in poor overall performance in the case that some of the interactions between units are significant (see, Samyudia *et al*. [12], for example).

To tackle the performance issue while maintaining the simplicity of decentralized control, a methodology for multi-unit control design was proposed by Samyudia *et al*. [13] and further extended in Samyudia *et al*. [12]. The proposed methodology consists of three steps, namely, decomposition, interaction analysis and design. A short summary of the three steps are presented in the sequence. More details can be found in Samyudia *et al*. [12] and Samyudia [14].

The decomposition step is composed of two methods, namely, physical decomposition (PD) and decomposition across units (DAU). In PD, a multi-unit process is decomposed based on the physical unit operations, and the interactions between units are represented by recycle streams. In DAU, the plant decomposition is performed by considering the dynamics of the variables to be controlled with no regard to the physical units in which these variables occurs. As a result, a set of alternative plant decompositions can be produced.

In the analysis step, the alternative plant decompositions obtained in the decomposition step are examined. The best plant decomposition is selected based on a gap metric criterion.

A design model G_d in the set of the alternative plant decompositions may be coprime factorized. The left normalized coprime factorization of G_d can be represented as:

$$G_d = M_d^{-1} N_d$$

where M_d, $N_d \in RH_\infty$.

Furthermore, the left normalized coprime factorization of the linearized model G can always be represented as:

$$G = M^{-1}N = (M_d + \Delta_M)^{-1}(N_d + \Delta_N)$$

where Δ_M and Δ_N are the coprime factor uncertainty which represents the interaction between subsystems. Then the gap $\delta(G_d, G)$ between G and G_d is defined as the maximum of the two directed gaps $\delta_t(G_d,G)$ and $\delta_t(G,G_d)$ (see Georgiou and Smith [2] for details).

Let the maximum stability margin be defined as:

$$b_{\max} = \left(\inf_{k_d\ stabilizing} \left\| \begin{bmatrix} K_d \\ I \end{bmatrix} (I - G_d K_d)^{-1} [G_d \quad I] \right\|_\infty \right)^{-1}. \qquad (3)$$

Then the following theorem holds:

Theorem 1. (Samyudia *et al*. [12])

Suppose the maximum stability margin for a design model G_d is b_{max} and let $\beta = \delta(G_d, G)$. There exists a decentralized stabilizing controller K_d for G_d that stabilizes the overall system G if $\beta < b_{max}$.

The indicator β represents the gap between the design model G_d and the full model G. Obviously, a smaller β means the design model is closer to the full model, hence a better model for controller design. Note that the maximum stability margin for G_d and the indicator β are calculated from open-loop information only. Therefore, the best plant decomposition can be determined by examining β and b_{max} for every design model in the set of alternative plant decompositions.

A suitable decentralized controller can be obtained in the design step by simply solving the optimal robustness problem in theorem 1.

To achieve further performance specifications, a suitable weighting transfer matrix W can be pre-selected to shape the full model G and the design model G_d. The best plant decomposition is selected by examining the indicators β and b_{max} for GW and G_dW. Then a decentralized controller transfer matrix K_d can be designed for the shaped design G_dW. Finally the weighting should be absorbed by the controller, hence the decentralized controller transfer matrix for the full model G should be WK_d.

2.2 Extension of the methodology to an operating region

Since the linearized model G is an approximation of the nonlinear plant at the specific operating point, it is only valid in a neighborhood of the operating point. If there are disturbances in the nonlinear plant, it is possible for the operating point to be shifted across the boundary of the valid neighborhood, such that either the linearized model G or the best decomposition G_d obtained at the original operating point may be invalid.

To tackle this situation, the methodology proposed above needs to be extended to an operating region. Specifically, the possible disturbance sources and their corresponding extents can be identified *a priori*. The joint efforts of the manipulated variables and the disturbances will lead to a potential operating region for the nonlinear plant.

Once the potential operating region is obtained, a simple grid method can be used in this region. Note that every grid point represents a "local" linearized model for the nonlinear plant at that specific point. Therefore, the above-proposed methodology can be applied to every grid point to get the best "local" decomposition. Furthermore, neighboring grids with the same best decomposition structure can be joined together to separate the whole operating region into several sub-regions. Since every sub-region admits the same best decomposition structure, a unified decentralized controller structure can be designed for the sub-region.

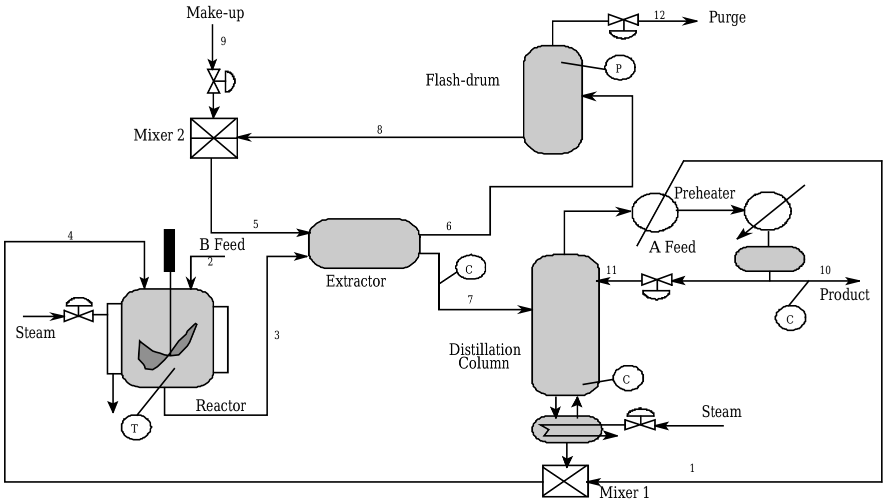

Figure 1. A reactor/separation process

3 Application to A Reactor/Separation Process

The reactor/separation process shown in Figure 1 has five controlled variables and five manipulated variables. The controlled variables are the reactor temperature T_R, the raffinate composition x_{G7}, the product composition x_D, the bottom composition x_B and the flash-drum pressure P. The five manipulated variables are the steam flowrate S, the make-up flowrate Mk, the reflux flowrate L, the boilup rate V and the purge flowrate F_{12}. The process was originally described by Samyudia [14].

It is assumed that the disturbance sources have been identified. The disturbance variables are the A feed flowrate F_1, A feed temperature T_{F0}, B feed temperature T_2, steam temperature T_{J0}, the bottom flowrate B, the bottom temperature T_B and the recycle-flash flowrate F_8.

For simplicity and clarity, it is further assumed that only the A feed flowrate F_1 and the bottom flowrate B change from 10 kmol/hr to 20 kmol/hr. The remainder of the disturbance variables are unchanged.

The emphasis in this paper is on the decomposition and the analysis steps only. Further discussions about the controller design will be reported in subsequent work.

3.1 Decomposition

In this work, nine decompositions were generated for the five unit reactor/separation process, using physical decomposition and the decomposition across units. The summary of these nine decompositions is given in Table 1 at the end of the paper.

Since the disturbance variables F_1 and B change from 10 kmol/hr to 20 kmol/hr, a simple grid is obtained by increasing F_1 and B from 10 kmol/hr to 20 kmol/hr in 0.5 kmol/hr incremental steps.

3.2 Analysis

In this paper, the following weighting transfer matrix is chosen to shape the open-loop plant:

$$W = \begin{bmatrix} 2\times10^3 & 0 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 \\ 0 & 0 & 300 & 0 & 0 \\ 0 & 0 & 0 & 50 & 0 \\ 0 & 0 & 0 & 0 & 50 \end{bmatrix} \frac{s+5}{s(s+0.1)}. \quad (4)$$

The integral action in the weighting matrix is to ensure a zero steady state error. The zero is to adjust the roll-off rate in the region of the crossover frequencies and the pole 0.1 is to limit the roll-off at high frequencies. This design was in accordance with principles developed by Samyudia *et al.* [12].

A set of linearized models was generated for the grid points of the operating region. Figure 2 show the singular values of the shaped full system GW when F_1=15 kmol/hr and B=15 kmol/hr.

Overall, it was found that the candidates for the best decompositions were DAU7 and DAU8. Hence detailed analysis is concentrated on DAU7 and DAU8 only.

Figure 3 shows two differential planes over the defined operating region. One plane is constructed using the value of (b_{max} of DAU7 – the value of b_{max} of DAU8), the other one is drawn using the value of (β of DAU7 – the value of β of DAU8). From Figure 3, the b_{max} differential plane is rather smooth and is very close to zero. Hence it may be assumed that there is no significant difference between the maximum stability margin of DAU7 and that of DAU8 over the whole operating region. However, the β differential plane behaves differently in different sub-regions.

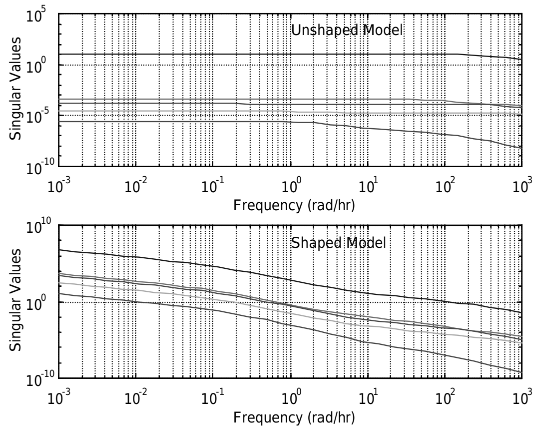

Figure 2. Singular values of the shaped and unshaped plant.

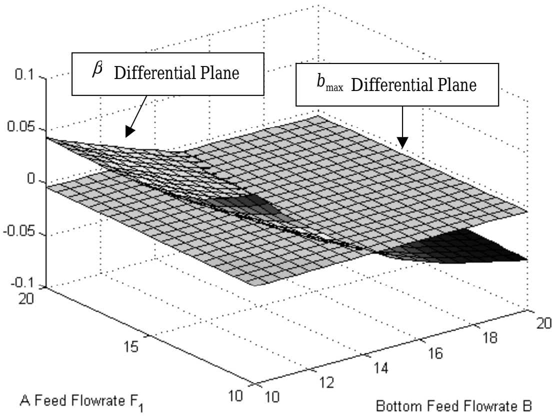

Figure 3. Planes for b_{max} *(DAU7) –* b_{max} *(DAU8) and for β (DAU7) – β (DAU8)*

Figure 4 shows the zero crossing curve of the β differential plane. Obviously, β of DAU7 is greater than β of DAU8 in sub-region 1, while the situation is reversed in sub-region 2. Since indicator β represents the closeness of the shaped design model to the shaped full model, it is straightforward to see that DAU8 is the best decomposition for sub-region 1 while DAU7 is the best decomposition for sub-region 2.

Figure 5 shows the b_{max} and β planes of DAU7 over the whole operating region. Note that the two planes cross over in the low left corner which means $\beta > b_{max}$ in this corner. It is unsure whether DAU7 is stable in this corner, since the sufficient condition of theorem 1 is not applicable.

Figure 6 shows the b_{max} and β planes of DAU8 over the whole operating region. Like DAU7, the two planes cross over in the low left corner. However, the situation for DAU8 is better that for DAU7 as the corner in which stability is not guaranteed is insignificant. This further confirms that DAU8 is the best decomposition for sub-region 1.

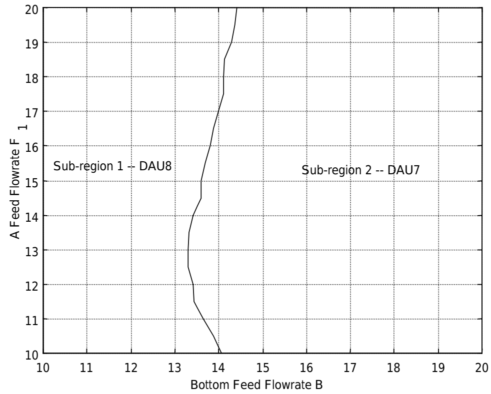

Figure 4. Zero crossing curve of β (DAU7) – β (DAU8) plane

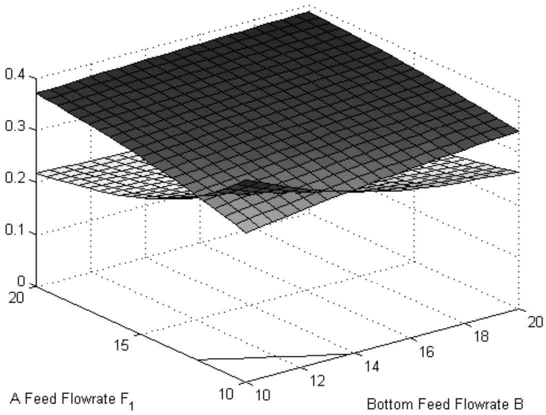

Figure 5. b_{max} *and β planes for DAU7*

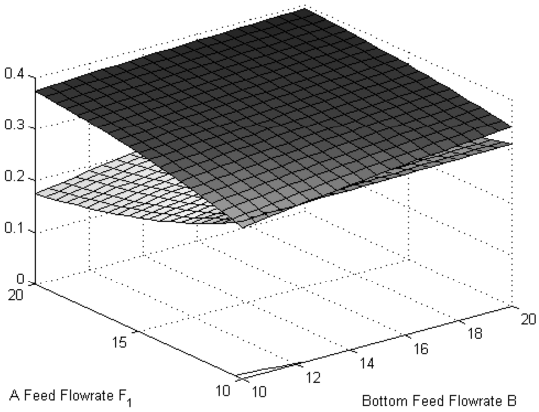

Figure 6. b_{max} *and β planes for DAU8*

3.3 Design

Decentralized controllers were designed based on the shaped DAU7 and DAU8 design models respectively over the two sub-regions. Closed-loop simulations were carried out by applying the obtained controllers to the nonlinear model.

3.3.1 Sub-region 1

Two decentralized controllers were designed for the shaped DAU7 and DAU8 design models at the operating point which is produced by letting F_1=15.5 kmol/hr and B=12 kmo/hr and normal values of the manipulated variables. Closed-loop simulations were performed using the two decentralized controllers at the specific operating point. For simplicity, only the flash pressure responses are depicted here. Figure 7 shows the flash pressure responses to a 26% change in the A feed flowrate.

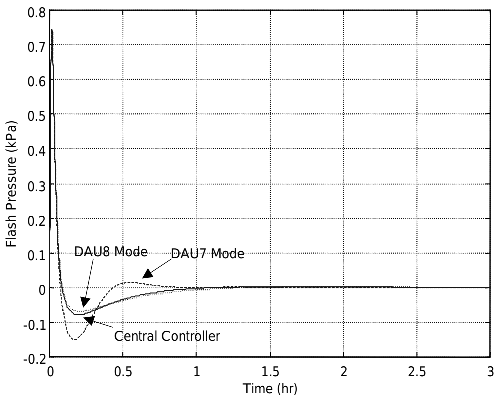

Figure 7. Flash pressure responses to 26% change in the A feed flowrate.

The gap indicator β indicates the closeness between a particular decomposition and the full model. As this is a sub-region 1 operating point, β of the DAU8 decomposition is smaller than β of the DAU7 decomposition, i.e., DAU8 decomposition is "closer" to the full model in the gap metric sense. Since the central controller is designed based on the full model, it is expected that the decentralized controller based on the shaped DAU8 design model should result in a similar response to the central controller. Indeed, as observed from Figure 7, the response under DAU8 decentralized control is very close to the response under fully centralized control. In contrast, the response under DAU7 decentralized control has significant differences with the response under fully centralized control. Overall, the simulation confirms that DAU8 is the best decomposition for sub-region 1.

3.3.2 Sub-region 2

Similarly, two decentralized controllers were designed for the shaped DAU7 and DAU8 design models at the operating point which is produced by letting F_1=15.5 kmol/hr and B=17 kmol/hr and normal values of the manipulated variables. Figure 8 shows the flash pressure responses to a 26% change in the A feed flowrate.

As this is a sub-region 2 operating point, it is expected that the decentralized controller based on the shaped DAU7 design model should result in a closer response to the central controller. From Figure 8, it is observed that the response under DAU7 decentralized control is closer to the response under fully centralized control. Contrary to the sub-region 1 case, the response under DAU8 decentralized control now displays significant differences to the response under fully centralized control. Again, the observation coincides with the values of β for DAU7 and β for DAU8 in this region. Overall, it also confirms that DAU7 is the best decomposition for sub-region 2.

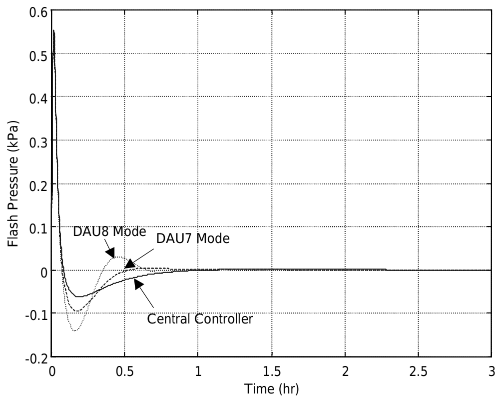

Figure 8. Flash pressure responses to 26% change in the A feed flowrate.

It is further noticed that the responses under the fully centralized control in both Figures 7 and 8 take the same shape while the shapes of other responses change according to the operating points. This is due to the interactions between the units.

4 Conclusions

This paper has proposed a new approach to decentralized control design for nonlinear multi-unit plants. The proposed method involves evaluating a performance criterion for a set of alternative plant decompositions in an operating region. Based on the values of the stability and performance indicators of the performance criterion, sub-regions of the operating space are determined with each sub-region admitting the same best local plant decomposition. Thus local decentralized controllers can be designed using the best local plant decompositions.

The proposed method has been applied to a reactor/separator process. Simulation study of the process further verifies the sub-region selections.

Further research should be concentrated on two aspects: 1). use a suitable stability criterion as a major tool for sub-region separation; 2). improve local decentralized controller design by considering the "edge" effect and further consider semi-global controller design.

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Table 1. Alternative plant decompositions for reactor/separation process

MODE	SUBSYSTEM	CONTROLLER AND MANIPULATED VARIABLES	CONTROLLER COMPLEXITY
SA	(1). Reactor+Preheater; (2). Extractor; (3). Distillation Column; (4). Flash-drum	(1). T_R and S; (2). x_{G7} and Mk; (3). x_D, x_B and L, V; (4). P and F_{12}	(1). SISO; (2). SISO; (3). 2x2 MIMO; (4). SISO;
DAU1	(1). Reactor+Preheater; (2). Extractor; (3). Distillation Coulmn+Flash-drum	(1). T_R and S; (2). x_{G7} and Mk; (3). x_D, x_B, P and L, V, F_{12}	(1). SISO; (2). SISO; (3). 3x3 MIMO;
DAU2	(1). Reactor+Preheater+Extractor; (2). Distillation Column; (3). Flash-drum	(1). T_R, x_{G7} and S, Mk; (2). x_D, x_B and L, V; (3). P and F_{12}	(1). 2x2 MIMO; (2). 2x2 MIMO; (3). SISO
DAU3	(1) Reactor+Preheater++Extractor+ Distillation Column; (2). Flash-drum	(1). T_R, x_{G7}, x_D, x_B and S, Mk, L, V; (2). P and F_{12}	(1). 4x4 MIMO; (2). SISO
DAU4	(1). Reactor+Preheater; (2). Extractor+Flash-drum; (3) Distillation Column	(1). T_R and S; (2). x_{G7}, P and Mk, F_{12}; (3). x_D, x_B and L, V	(1). SISO; (2). 2x2 MIMO; (3). 2x2 MIMO
DAU5	(1). Reactor; (2). Extractor+Flash-drum; (3). Distillation Column+Preheater	(1). T_R and S; (2). x_{G7}, P and Mk, F_{12}; (3). x_D, x_B and L, V	(1). SISO; (2). 2x2 MIMO; (3). 2x2 MIMO
DAU6	(1). Reactor+Extractor+Flash-drum; (2). Distillation Column+Preheater	(1). T_R, P, x_{G7} and S, Mk, F_{12}; (2). x_D, x_B and L, V	(1). 3x3 MIMO; (2). 2x2 MIMO
DAU7	(1). Reactor+Preheater+Distillation Column (2). Extractor+Flash-drum	(1). T_R, x_D, x_B and S, L, V; (2). x_{G7}, P and Mk, F_{12}	(1). 3x3 MIMO; (2). 2x2 MIMO;
DAU8	(1). Reactor+Preheater (2). Extractor+Distillation Column+Flash-drum	(1). T_R and S; (2). xG7, xD, x_B, P and Mk, L, V, F_{12}	(1). SISO; (2). 4x4 MIMO