C

Analytical Comparison of Interconnection Methods

In this chapter, we shed some light on the costs of the different interconnection methods. As elaborated in Chapter 9 (Section 9.2), there are two basic interconnection methods:

- A *direct line* to connect two interconnection partners directly.
- An *Internet Exchange Point (IXP)* that a larger number of providers are connected to. A large number of interconnections can be realized via a single IXP. Three theoretical types of IXPs can be distinguished by whether they are based on
  - ○ an exchange router.
  - ○ an exchange Local Area Network (LAN) (switch).
  - ○ an exchange Metropolitan Area Network (MAN).

We use some very simple analytical models to investigate the cost structure of the different IXP types (Section C.1), to investigate when the use of an IXP is cost efficient (Section C.2) and which type of IXP is more cost efficient, depending on the number of connected parties (Section C.3).

C.1 Internet Exchange Point Cost Models

In this section, simple cost models for the different IXP structures are elaborated. Table C.1 lists the variables and parameters used in these models.

C.1.1 Exchange Router

If an IXP uses an exchange router, each Internet Network Service Provider (INSP) has to spend the full costs for the lease of the connection line (c_L) to the IXP and part of the costs for the central exchange router (c_{ER}) at the IXP location. The cost function for the exchange router model shown in Figure C.1 is

$$c_{INSP}^{ExchRouter} = c_L + \frac{1}{N} \cdot c_{ER} \tag{C.1}$$

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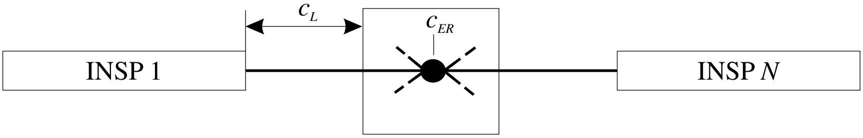
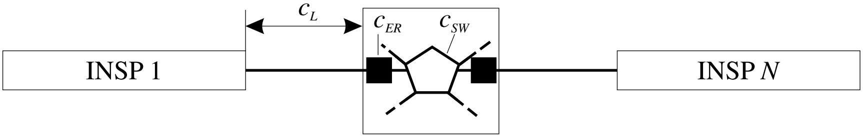
Table C.1 Variables and Parameters of the Cost Models

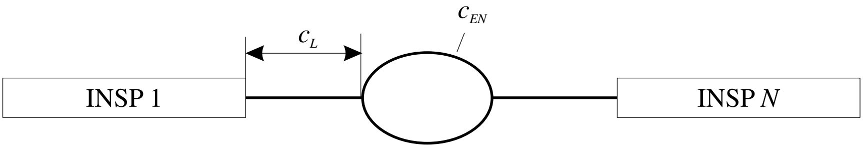
N	Number of INSPs
c_{INSP}	Total cost of one INSP within an existing set of N INSPs
c_{ER}	Cost for one exchange router
c_L	Cost for a connection line
c_{EN}	Costs of the exchange network
c_{SW}	Costs for a switch in the exchange network



(a) Exchange Router



(b) Exchange LAN



(c) Exchange MAN

Figure C.1 Internet Exchange Point Costs Models

The exchange router model is the most cost efficient structure for IXP interconnection, but is vulnerable to congestion and has some structural drawbacks additionally. It has insufficient support for Quality of Service (QoS) as well as individual peering and routing policies. For example, the IXP managing the exchange router selects a single route to one destination that then has to be used by all connected providers (as seen in Figure C.2). This is a huge drawback for INSPs and therefore the exchange router is practically not used nowadays.

C.1.2 Exchange LAN

For the exchange LAN structure (see Figure C.3), N lines are needed in total to connect the N INSPs to the IXP LAN. Additionally, one edge router per INSP is necessary. The

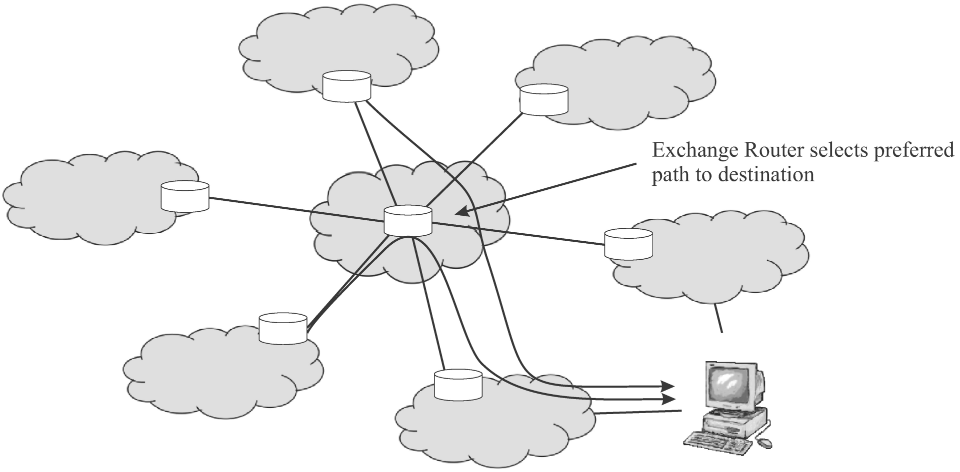


Figure C.2 Exchange Router Structure

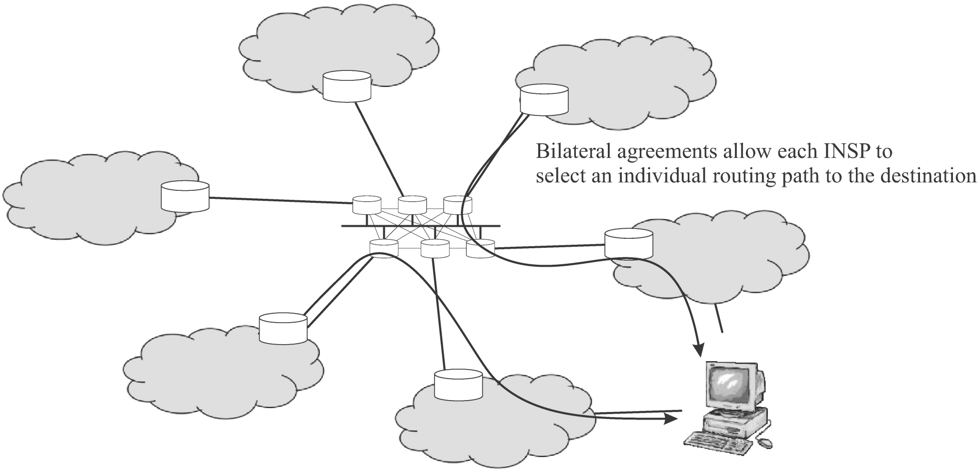


Figure C.3 The Exchange LAN Structure

edge router is owned by each INSP. It enables the INSP to choose its own routing and QoS policies and to decide which INSP to cooperate with.

The IXP has to operate one central network switch (c_{SW}). This results in the following cost function, see also Figure C.1:

$$c_{INSP}^{LAN} = c_L + c_{ER} + \frac{1}{N} \cdot c_{SW} \tag{C.2}$$

This model of exchange colocation enables connection with diverse access media, as the provider's colocated router undertakes the media translation between access link protocol

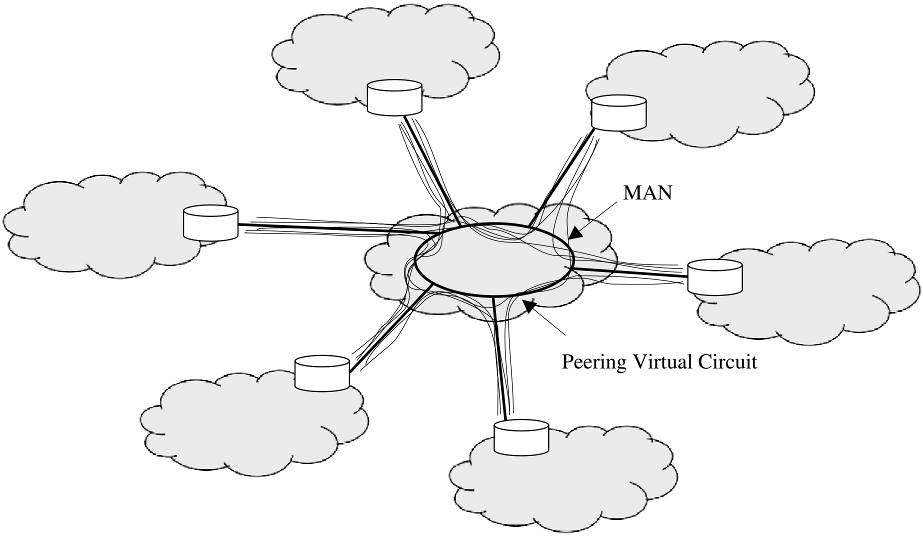


Figure C.4 The Exchange MAN Structure

and the common exchange protocol (usually Border Gateway Protocol (BGP), see Rekhter and Li (1995)). A drawback of this model is that of imposed traffic[1].

C.1.3 Exchange MAN

The costs of an exchange MAN IXP (see Figure C.4) consist of the line costs to connect the IXP to the next entry point of the MAN. These line costs c_L are typically smaller than those in the exchange LAN model because the geographical distance to the next access point of the distributed MAN will typically be smaller than that to the central LAN. This is a cost shift from the INSP to the IXP which results in lower line costs for the Internet Service Provider (ISP) but higher access costs for connecting to the IXP network.

The resulting cost function for the exchange MAN model is as follows, see also Figure C.1:

$$c_{INSP}^{MAN} = c_L + \frac{1}{N} \cdot c_{EN} \tag{C.3}$$

Exchange MAN structures enforce the use of a uniform access technology, see Huston (1999a).

C.2 Cost Efficiency of an Internet Exchange Point

It is quite intuitive that for a larger number of INSPs a fully meshed interconnection structure where every INSP is directly connected with all others (see Figure 9.2 (b)) is

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[1] In the absence of a defensive mechanism a router accepts all traffic forwarded to it, even if there are no interconnection agreements between the two parties. Therefore, exchange routers require careful configuration management to ensure that the traffic matches the interconnection agreements, see Huston (1999a).

not as cost effective as a structure where all INSPs are connected with each other indirectly via an IXP. With a simple analytical model, we show now that an IXP is already cost effective for a very small number of INSPs.

We compare the costs of a fully meshed structure without an IXP (C.4) with those of a structure using an IXP. The IXP is modelled as exchange LAN in (C.5).

$$c_{INSP}^{FM} = c_L^{FM} \cdot \frac{N-1}{2} \tag{C.4}$$

$$c_{INSP}^{LAN} = c_L^{LAN} + c_{ER} + \frac{1}{N} \cdot c_{SW} \tag{C.5}$$

The terms c_L express the average line costs. We assume that they are proportional to the Euclidean distance d between the connecting parties:

$$c_L = p_c \cdot d \tag{C.6}$$

p_c is the price per distance; it is assumed to be identical for the fully meshed and the IXP LAN models. The distance d will be different for the two models. We elaborate the distance assuming that the INSPs are uniformly distributed over a quadratic, circular area, see Figure C.5:

1. Let the positions of the INSPs be distributed uniformly in a *quadratic area* with the dimension $2R$, as illustrated in Figure C.5. It is assumed that the IXP is located in the middle of the distribution.
   (a) The expected Euclidean distance *between two INSPs i and j* is defined as

$$d_q^{FM} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} = \sqrt{(\Delta x)^2 + (\Delta y)^2} \tag{C.7}$$

The expected distance between two uniformly distributed independent random variables x, y on interval [0,1] is

$$\int_0^1 \left(x \cdot \frac{x}{2} + (1-x) \cdot \frac{1-x}{2} \right) dx = 1/3 \tag{C.8}$$

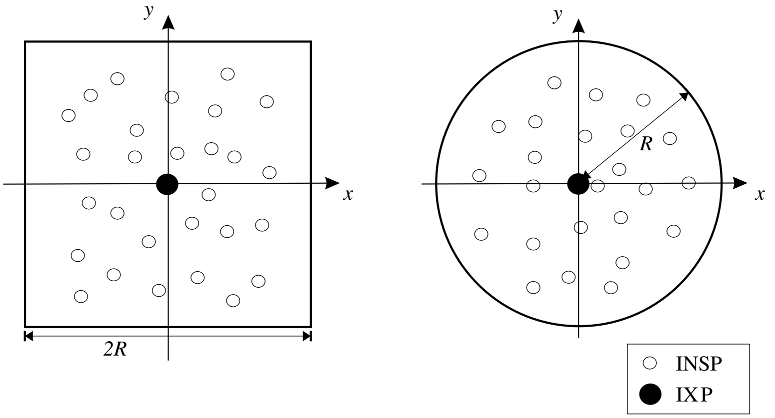

Figure C.5 Quadratic and Circular Distribution therefore, $\Delta x = \Delta y = \frac{2}{3}R$ and the average distance d_q^{FM} between two INSPs in the quadratic model is

$$d_q^{FM} = \frac{\sqrt{2} \cdot 2R}{3} \tag{C.9}$$

(b) The expected Euclidean distance d_q^{LAN} *between one INSP i and the IXP* is defined accordingly as

$$d_q^{LAN} = \sqrt{(x_i - x_{IXP})^2 + (y_i - y_{IXP})^2} \tag{C.10}$$

$$= \sqrt{(\Delta x')^2 + (\Delta y')^2} \tag{C.11}$$

The expected distance between a uniformly distributed random variable and the origin on interval [-1, 1] is

$$\int_{-1}^{0} -\frac{x}{2}\,dx + \int_{0}^{1} \frac{x}{2}\,dx = 1/2 \tag{C.12}$$

therefore, $\Delta x' = \Delta y' = \frac{1}{2} \cdot R$ and the average distance d_q^{LAN} between an INSP and the IXP in the quadratic model is

$$d_q^{LAN} = \frac{R}{\sqrt{2}} \tag{C.13}$$

2. Let the positions of the INSPs be distributed uniformly in a *circular area* with diameter $2R$, as illustrated in Figure C.5. Again, it is assumed that the IXP is located in the middle of the distribution.

(a) The expected Euclidean distance d_c^{FM} *between INSPs i and j* is defined as

$$d_c^{FM} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{C.14}$$

$$\text{with } p_i = (x_i, y_i) \text{ and } p_j = (x_j, y_j)$$

Let $C = \{p = (x, y) \mid x^2 + y^2 \leq R\}$ denote the set of points in a circle with radius R. The expected distance between two INSPs in the circular model is (see Santaló (2004))

$$\begin{aligned} d_c^{FM} &= \left(\frac{1}{\pi}\right)^2 \int_C \int_C d_{ij}(p_i, p_j)\,dp_i\,dp_j \\ &= \frac{128}{45\pi} R = 0.9054 \cdot R \end{aligned} \tag{C.15}$$

(b) The expected Euclidean distance d_c^{LAN} *between an INSP and the IXP* is

$$d_c^{LAN} = \frac{\int_0^R 2\pi r \cdot r\,dr}{\int_0^R 2\pi r\,dr} = \frac{2}{3}R \tag{C.16}$$

Now the equations (C.4) and (C.5) can be compared with each other to calculate the value of N at which the exchange LAN structure is more cost effective than the fully meshed structure:

$$c_{INSP}^{FM} \geq c_{INSP}^{LAN} \tag{C.17}$$

$$(N-1) \cdot \frac{c_L^{FM}}{2} \geq c_L^{LAN} + c_{ER} + \frac{1}{N} \cdot c_{SW} \tag{C.18}$$

$$0 \leq N \cdot (N-1) \cdot \frac{c_L^{FM}}{2} + N(-c_L^{LAN} - c_{ER}) - c_{SW} \tag{C.19}$$

$$0 \leq N^2 \cdot \frac{c_L^{FM}}{2} + N(-\frac{c_L^{FM}}{2} - c_L^{LAN} - c_{ER}) - c_{SW} \tag{C.20}$$

with $\frac{c_L^{FM}}{2} \geq 0$ (C.20) is an open parable $f(N) = aN^2 + bN + c$ with the minimal $N = -\frac{b}{2a}$

$$N \geq -\frac{-\frac{c_L^{FM}}{2} - c_L^{LAN} - c_{ER}}{2 \cdot \frac{c_L^{FM}}{2}} \tag{C.21}$$

$$N \geq \frac{1}{2} + \frac{c_L^{LAN}}{c_L^{FM}} + \frac{c_{ER}}{c_L^{FM}} \tag{C.22}$$

With $c_L^{type} = p_c \cdot d^{type}$

$$N \geq \frac{1}{2} + \frac{d^{LAN}}{d^{FM}} + \frac{c_{ER}}{p_c d^{FM}} \tag{C.23}$$

For the quadratic distribution

$$N_q \geq \frac{5}{4} + \frac{c_{ER}}{\frac{\sqrt{2} \cdot 2R}{3} \cdot p_c} \tag{C.24}$$

For the circular distribution

$$N_c \geq \frac{1}{2} + \frac{15}{64} \cdot \pi + \frac{c_{ER}}{\frac{128}{45\pi} R \cdot p_c} \tag{C.25}$$

Assuming that the exchange router is a Cisco Catalyst 7206 with an approximate value of $c_{ER} = 20{,}000$ EUR and the fibre price per kilometre and year of approximate $p_c = 1{,}000$ EUR/km. Assuming further that the connecting INSPs are within the boundaries of a city the size of Frankfurt/Main, the value of R is approximately 7 km. These assumptions lead to the value of N at which the exchange LAN structure is more cost efficient.

$$N_q \geq 4.28 \tag{C.26}$$

$$N_c \geq 4.39 \tag{C.27}$$

With at least five connecting INSPs, the exchange LAN structure is already more cost efficient than the fully meshed structure. While this result is based on a lot of assumptions and varies depending on the chosen R and the assumed costs, it still points out well that using an IXP is cost efficient for a very small number of providers within a city's boundary. With an increasing R the number of providers N becomes even smaller.

C.3 LAN versus MAN IXP Structure

Next, we compare the exchange LAN and MAN structures for a single IXP. For simplification purposes, it is assumed that the exchange MAN forms a circle with radius R' through the circular area of the previous section so that the expected distance d_c^{MAN} between an INSP and the MAN is $R/4$.

$$c_{INSP}^{LAN} = p_c \cdot \frac{2R}{3} + c_{ER} + \frac{1}{N} \cdot c_{SW} \tag{C.28}$$

$$c_{INSP}^{MAN} = p_c \cdot \frac{R}{4} + \frac{1}{N} \cdot c_{EN} \tag{C.29}$$

Combining equations (C.28) and (C.29) leads to the value of N at which the exchange MAN structure is more cost effective than the exchange LAN:

$$c_{INSP}^{LAN} \geq c_{INSP}^{MAN} \tag{C.30}$$

$$p_c \cdot \frac{2R}{3} + c_{ER} + \frac{1}{N} \cdot c_{SW} \geq \frac{1}{N} \cdot c_{EN} + p_c \cdot \frac{R}{4} \tag{C.31}$$

with $c_{EN} \gg c_{SW}$

$$N \geq \frac{c_{EN}}{\frac{5}{12} \cdot p_c \cdot R + c_{ER}} \tag{C.32}$$

Let us assume that the exchange MAN has costs roughly similar to the DE-CIX IXP in Frankfurt. DE-CIX has three main locations with redundant switches whose approximate value is 300,000 EUR and about 20 km fibre lines connect the locations with each other. For a city the size of Frankfurt, the value of R is 7 km. These assumptions lead to the value of N at which the exchange MAN structure is more cost efficient.

$$\begin{aligned} N &\geq \frac{3 \cdot 2 \cdot 300{,}000 + 1{,}000 \cdot 20}{\frac{5}{12} \cdot 1{,}000 \cdot 7 + 20{,}000} \\ &\geq 79.42 \\ &\geq 80 \end{aligned}$$

When 80 or more INSPs use the IXP, the exchange MAN structure is more cost efficient than the exchange LAN structure. As an example, consider the real DE-CIX which is mostly a MAN and has currently 128 connected customers (see German Internet Exchange DE-CIX (2004)), which is more than enough for this simple model to make exchange MAN cost efficient.

Next, we assume that the exchange MAN has costs similar to the London Internet Exchange (LINX) IXP in London. LINX has four main locations with redundant switches and five smaller locations with small redundant switches with approximately 100 km fibre lines connecting the locations with each other. The costs of small switches are approximately 100,000 EUR and the costs of bigger switches are approximately 300,000 EUR. For a city the size of London, the value of R is 25 km. These assumptions lead to the value of N at which the exchange MAN structure is more cost efficient.

$$\begin{aligned} N_q &\geq \frac{4 \cdot 2 \cdot 300{,}000 + 5 \cdot 2 \cdot 100{,}000 + 1{,}000 \cdot 100}{\frac{5}{12} \cdot 1{,}000 \cdot 25 + 20{,}000} \\ &\geq 115.07 \\ &\geq 116 \end{aligned}$$

The difference is that DE-CIX involves greater network costs which are partly offset by the greater area covered with the exchange MAN structure. The LINX is mostly a MAN and at the time of writing had 143 connected customers (see LINX (2003)) and is cost efficient within the limitations of this simple model.