Tijdschrift van het NERG

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DE VERENIGING NERG

Het NERG is een wetenschappelijke vereniging die zich ten doel stelt de kennis en het wetenschappelijk onderzoek op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie te bevorderen en de verbreiding en toepassing van die kennis te stimuleren.

BESTUUR

LIDMAATSCHAP

Voor het lidmaatschap wende men zich via het correspondentie-adres tot de secretaris of via de NERG website: http://www.nerg.nl. Het lidmaatschap van het NERG staat open voor hen, die aan een universiteit of hogeschool zijn afgestudeerd en die door hun kennis en ervaring bij kunnen dragen aan het NERG. De contributie wordt geheven per kalenderjaar en is inclusief abonnement op het Tijdschrift van het NERG en deelname aan vergaderingen, lezingen en excursies.

De jaarlijkse contributie bedraagt voor gewone leden € 43,- en voor studentleden € 21,50. Bij automatische incasso wordt € 2,- korting verleend. Gevorderde studenten aan een universiteit of hogeschool komen in aanmerking voor het studentlidmaatschap. In bepaalde gevallen kunnen ook andere leden, na overleg met de penningmeester voor een gereduceerde contributie in aanmerking komen.

HET TIJDSCHRIFT

Het tijdschrift verschijnt vijf maal per jaar. Opgenomen worden artikelen op het gebied van de elektronica, signaalbewerking, communicatie- en informatietechnologie. Auteurs, die publicatie van hun onderzoek in het tijdschrift overwegen, wordt verzocht vroegtijdig contact op te nemen met de hoofdredacteur of een lid van de Tijdschriftcommissie.

TIJDSCHRIFTCOMMISSIE

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ISSN 03743853

INHOUD

Van de redactie

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Het leven van een hoofdredacteur gaat niet over rozen. Het ene moment weet je niet hoe je een nummer van het Tijdschrift gevuld moet krijgen, het volgende moment (in dat stadium verkeren we als redactie nu) heb je geen idee waar je de tijd vandaan moet halen om al het materiaal te verdelen over de verschillende nummers en hoe je die nummers vervolgens op tijd de deur uit krijgt. U bent op deze plaats al meer dan eens getuige geweest van dergelijke "klaagzangen". Laten we het daarom deze keer, met de naderende lente voor de deur, eens van de zonnige kant bekijken. En - laten we wel wezen - de zonnige kant van dit werk heeft toch nog altijd de overhand. Dat van het "niet over rozen gaan" dient dan ook met een behoorlijke korrel zout genomen te worden en moet meer gezien worden als een poging om eens op een andere manier te beginnen dan met het standaard "Voor u ligt alweer het eerste nummer van…..".

Het "van de redactie" wordt altijd als laatste geschreven en als hoofdredacteur heb je dan dat voldane gevoel dat het weer gelukt is een nummer van het Tijdschrift uit te brengen. Alle (relatieve) hobbels en hindernissen in het proces om zover te komen worden dan op slag vergeten. Zelf denk ik dat dit gevoel voor een man de beste gevoelsbenadering is voor het baren van een kind, maar ervaringsdeskundigen verzekeren me dat ik absoluut geen idee heb waarover ik spreek. Laat ik me daarom beperken tot de inhoud van dit nummer van het Tijdschrift.

We vangen in dit eerste nummer van jaargang 2003 aan met waar we in 2002 zijn opgehouden: De Nederlandse bijdragen aan de 25th ESA Antenna Workshop on Satellite Antenna Technology. Deze workshop vond in september 2002 plaats in Noordwijk en werd georganiseerd in samenwerking met, onder andere, het NERG.

We gaan na afronding van deze bijdragen verder met de Nederlandse bijdragen aan weer een ander congres. Jaarlijks houdt de "Federation of Telecommunications Engineers of the European Community" (FITCE) een congres over actuele onderwerpen in de telecommunicatie. In 2002 vond het 41ste FITCE congres plaats van 4 tot en met 7 September in Genua. Thema van het congres was: "Evolving Networks: Service Opportunities and Market Realities". De lezingen waren georganiseerd in drie dagen met als onderwerpen respectievelijk: From Circuit-Switced to IP-Based Networks, Broadband Solutions for the last mile en Mobile communications in the Future. Nederland was ook deze keer goed vertegenwoordigd met vier sprekers, welke hun lezingen herhaald hebben voor de NERG geïnteresseerden tijdens de themabijeenkomst 02/06. In het Tijdschrift van het NERG zal verslag gedaan worden van de Nederlandse bijdragen. De eerste twee bijdragen treft u aan in dit nummer. De resterende twee zult u niet in nummer 2 terugvinden maar in nummer 3. Nummer 2 zal namelijk in het teken staan van de Vederprijs.

Als laatste treft u in dit nummer het overzicht aan van de proefschriften 2002.

Ik wens u veel leesplezier toe en wil u ook nog met klem attenderen op de oproep aan de binnenkant van de omslag van het Tijdschrift.

A Coupled Feed-Radiator-Frequency Selective Surface Model for the Next Generation Active Phased Array Systems

B.J. Morsink, G.H.C. van Werkhoven and A.G. Tijhuis

Introduction

Modern radar systems are based upon active phased phased arrays, such as the SMART-L long range 3D volume search radar and the APAR multi-function search/track and missile guidance radar. These radars, which are recently delivered to Dutch and German navies, use the electronic scanning ability of the phased arrays for fast beam positioning and pattern generation with flexible beam types in both transmit and receive mode.
Trends for next generation radar systems set additional requirements for the antenna front-ends, such as improved antenna performance by countering interference (EMI) problems and reduced sensor radar signature.

Within this context, and in collaboration with the Eindhoven University of Technology, a new type of array antenna is studied, the so-called multi-layer array antenna. Such an antenna is a flat multilayer structure that includes an array of radiators, for example cavity backed patches, and their feeding structures, and one or more frequency selective surfaces (FSS). More specific, but expressed in more general terms, a numerical model has been developed for the analysis of a stratified periodic electromagnetic field problem.

The model is based upon generalized transmission matrix equations. In this paper it is shown that this approach describes the field propagation in both the patch-enclosed cavity and the adjacent FSS layers. Full wave solutions over the layered structure can be obtained by either cascading the resulting scattering matrices, or by solving coupled differential equations, making use of the analytically available Green functions. The model is validated by comparing results against available commercial tooling such as HFSS. An arbitrary structure is analysed for its reflection and transmission properties.

FORMULATION OF THE PROBLEM

A single unit-cell of the configuration of interest is given in Fig. 1. It consists of three parts : a slot, box and a FSS. The slot is a waveguide with dimensions: width w_s and height h_s. It is filled with a material with $\varepsilon_r = 3$ and $\mu_r = 1$. The box is a waveguide with dimensions: width w_b , height h_b and depth d. It is filled with a material with $\varepsilon_r = 3$ and $\mu_r = 1$. The FSS is a periodic layered space. It consists of free space and contains an infinitely thin perfectly electric conducting patch with dimensions: width w_p and height h_p. The unit-cells are placed in a rectangular grid with basis vectors $\underline{d}_1$ and $\underline{d}_2$. From a transverse point of view, all parts of this structure are centered within the unit-cell.

The field problem will be solved using two different techniques. The first technique involves cascading scattering matrices obtained by solving the separate magnetic field integral equations (MFIE) for each transverse discontinuity. The second technique involves solving a coupled system of MFIE for all discontinuities at once. In both cases, we exploit the analytical knowledge of the spectral Green's function both for the waveguide as well as for the periodic layered space, which in fact are two examples of stratified electromagnetic field problems.

It is conventional to let the $\hat{z}$-axis point in the longitudinal direction. Accordingly, a so-called trans-

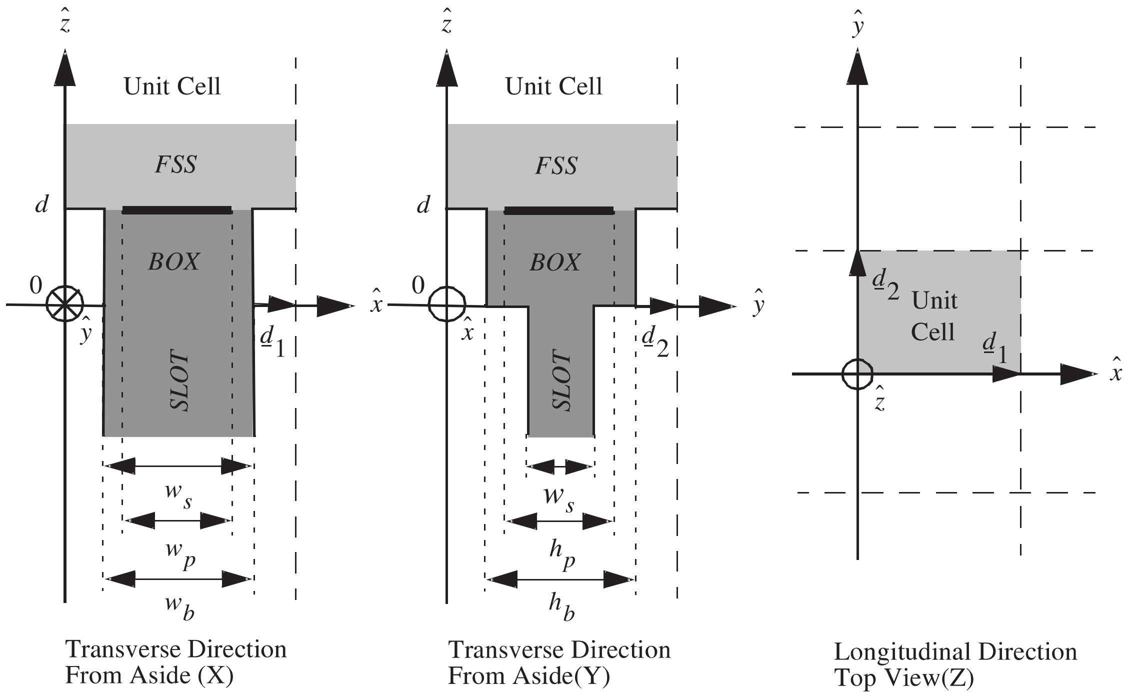


Figure 1: Description of the configuration of interest

verse plane is a plane for which z is arbitrary but fixed. In a given transverse plane the position is fully specified by the transverse part $\underline{\rho}$ of the position vector $\underline{r}$, which is given by

$$\underline{\rho}=\rho_x\hat{x}+\rho_y\hat{y} \qquad \underline{r}=\underline{\rho}+z\hat{z} \tag{1}$$

The configuration is characterised separately in the transverse and longitudinal direction. In the transverse direction, we allow for a periodic arrangement in a skew lattice defined by the transverse basis vectors $\underline{d}_1$ and $\underline{d}_2$ of so-called unit-cells. In the longitudinal direction, within a unit-cell but equal over all unit-cells, we allow for an arbitrary stratification. Within this stratification, we can either place a frequency selective surface (FSS) or a waveguide (WG), both containing an arbitrary number of homogeneous dielectric layers and/or shaped metal sheets. The electromagnetic field and current densities are written as functions of a combination of transverse components $\underline{\rho}$ and longitudinal components z in the point of observation $\underline{r}$.

$$\begin{aligned}\{\underline{E},\underline{H},\underline{J},\underline{M}\}(\underline{\rho},z)&=\{\underline{E},\underline{H},\underline{J},\underline{M}\}(\underline{\rho},z\hat{z})\\&=\{\underline{E},\underline{H},\underline{J},\underline{M}\}(\underline{r})\end{aligned} \tag{2}$$

The electromagnetic field and current densities can be written in terms of transverse $\{\underline{E}_t,\underline{H}_t,\underline{J}_t,\underline{M}_t\}$ and longitudinal $\{\underline{E}_z,\underline{H}_z,\underline{J}_z,\underline{M}_z\}$ components.

$$\begin{aligned}&\{\underline{E},\underline{H},\underline{J},\underline{M}\}(\underline{\rho},z)=\\&\{\underline{E}_t,\underline{H}_t,\underline{J}_t,\underline{M}_t\}(\underline{\rho},z)+\hat{z}\{\underline{E}_z,\underline{H}_z,\underline{J}_z,\underline{M}_z\}(\underline{\rho},z)\end{aligned} \tag{3}$$

The electromagnetic field and current densities, located at an infinitesimal close distance towards the left side of any interface $z = z_m$, are denoted by $\{\hat{\underline{E}}_m,\hat{\underline{H}}_m,\hat{\underline{J}}_m,\hat{\underline{M}}_m\}$. Those located at the right side are denoted by $\{\tilde{\underline{E}}_m,\tilde{\underline{H}}_m,\tilde{\underline{J}}_m,\tilde{\underline{M}}_m\}$

$$\begin{aligned}\{\hat{\underline{E}}_m,\hat{\underline{H}}_m,\hat{\underline{J}}_m,\hat{\underline{M}}_m\}(\underline{\rho})&=\lim_{z\to z_m}\{\underline{E},\underline{H},\underline{J},\underline{M}\}(\underline{\rho},-z)\\\{\tilde{\underline{E}}_m,\tilde{\underline{H}}_m,\tilde{\underline{J}}_m,\tilde{\underline{M}}_m\}(\underline{\rho})&=\lim_{z\to z_m}\{\underline{E},\underline{H},\underline{J},\underline{M}\}(\underline{\rho},z)\end{aligned} \tag{4}$$

Boundary conditions

Across certain boundary surfaces (see Fig. 2) in this configuration, the electromagnetic properties, and hence the electromagnetic field quantities, may exhibit a discontinuous behaviour. Since at those positions the field quantities are no longer continuously differentiable and the Maxwell's equations cease to hold. To overcome this problem, i.e. to ensure existence and uniqueness of the electromagnetic field quantities, the Maxwell's equations must be supplemented with boundary conditions that interrelate the field values at both sides of the surfaces. The surfaces $\bar{S}_a$ and $\bar{S}_b$ are composed of infinitely thin perfectly electric conducting material. Consequently, the boundary conditions across these interfaces are given by

$$\tilde{\underline{E}}_{t;a}=\underline{0}\,\forall\underline{\rho}\in\bar{S}_a \qquad \tilde{\underline{E}}_{t;b}=\underline{0}\,\forall\underline{\rho}\in\bar{S}_b \tag{5}$$

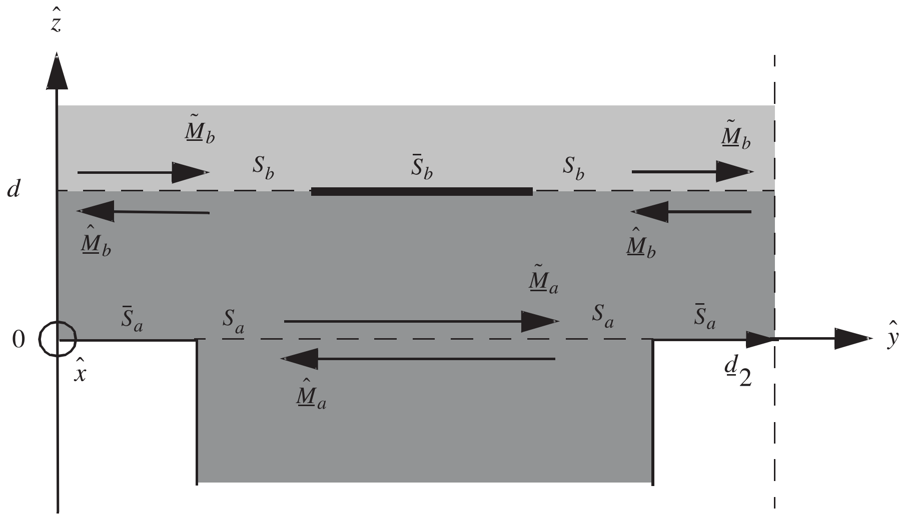


Figure 2: Boundary Conditions and the Equivalent Field Problem

The surfaces S_a and S_b represent the common openings. Consequently, the boundary conditions across these interfaces are given by

$$\begin{aligned} \underline{\hat{E}}_{t;a} &= \underline{\tilde{E}}_{t;a} \wedge \underline{\hat{H}}_{t;a} = \underline{\tilde{H}}_{t;a} \forall\, \underline{\rho} \in S_a \\ \underline{\hat{E}}_{t;b} &= \underline{\tilde{E}}_{t;b} \wedge \underline{\hat{H}}_{t;b} = \underline{\tilde{H}}_{t;b} \forall\, \underline{\rho} \in S_b \end{aligned} \tag{6}$$

Formulation of an equivalent field problem

The field equivalence is a principle by which real sources are replaced by equivalent sources. The fictitious sources are said to be equivalent within a region because they produce the same fields within that region. This principle is based on the uniqueness theorem which states that an electromagnetic field in a region is uniquely specified by the sources within that region plus a complete covering of either tangential components of the electric field or tangential components of the magnetic field or a combination of both over the boundary.

We introduce magnetic surface currents $\underline{\hat{M}}_a$ and $\underline{\tilde{M}}_a$ on interface S_a and $\underline{\hat{M}}_b$ and $\underline{\tilde{M}}_b$ on interface S_b. Interfaces S_a and S_b will be closed with infinitely thin perfectly electric conducting material. The equivalent problem has a unique solution if the following boundary conditions are satisfied. Across the surfaces $\bar{S}_a$ and $\bar{S}_b$ (see Fig. 2) boundary conditions (5) are translated into

$$\underline{\tilde{M}}_a = \underline{0} \forall \underline{\rho} \in \bar{S}_a \qquad \underline{\tilde{M}}_b = \underline{0} \forall \underline{\rho} \in \bar{S}_b \tag{7}$$

Across the surfaces S_a and S_b boundary conditions (6) are translated into

$$\begin{aligned} \underline{\tilde{M}}_a &= -\underline{\tilde{M}}_a \wedge \underline{\hat{H}}_{t;a} = \underline{\tilde{H}}_{t;a} \forall\, \underline{\rho} \in S_a \\ \underline{\tilde{M}}_b &= -\underline{\tilde{M}}_b \wedge \underline{\hat{H}}_{t;b} = \underline{\tilde{H}}_{t;b} \forall\, \underline{\rho} \in S_b \end{aligned} \tag{8}$$

Cascaded magnetic field integral equations

The magnetic surface currents are considered as the unknowns, which will be solved using a method of moment formulation. The continuity of magnetic field over the interfaces can be exploited further, by using the fact that the magnetic fields must be linear functions of the (yet unknown) magnetic sources. This can be done for each interface layer separately, leading to magnetic field integral equations per interface layer. The unknown magnetic currents must be solved by cascading S-matrices.

At interface S_a, the first part of boundary condition (8) can be written in terms of the unknown equivalent surface currents $\underline{\hat{M}}_a$ and $\underline{\hat{M}}_b$:

$$\begin{aligned} \underline{\hat{H}}_{t;a} = \underline{\tilde{H}}_{t;a} \Leftrightarrow \underline{\hat{H}}_{t;a}(\underline{\hat{M}}_a^{inc}, \underline{\hat{M}}_a) - \underline{\tilde{H}}_{t;a}(\underline{\tilde{M}}_a, \underline{\tilde{M}}_a^{inc}) = \\ = \underline{0} \forall \underline{\rho} \in S_a \end{aligned} \tag{9}$$

since the field solutions must be linear functions of the exitations. When applying the superposition principle and boundary condition (7), (9) can be rewritten as the following magnetic field integral equation with unknown surface current $\underline{\hat{M}}_a$

$$\begin{aligned} &\underline{\hat{H}}_{t;a}(\underline{0}, \underline{\hat{M}}_a) + \underline{\tilde{H}}_{t;a}(\underline{\hat{M}}_a, \underline{0}) = \\ &-\underline{\hat{H}}_{t;a}(\underline{\hat{M}}_a^{inc}, \underline{0}) + \underline{\tilde{H}}_{t;a}(\underline{0}, \underline{\tilde{M}}_a^{inc}) \forall \underline{\rho} \in S_a \end{aligned} \tag{10}$$

At interface S_b, the second part of boundary condition (8) can be written in terms of the unknown equivalent surface currents $\underline{\hat{M}}_b$ and $\underline{\tilde{M}}_b$.

$$\underline{\hat{H}}_{t;b} = \underline{\tilde{H}}_{t;b} \Leftrightarrow \underline{\hat{H}}_{t;b}(\underline{\hat{M}}_b^{inc}, \underline{\hat{M}}_b) - \underline{\tilde{H}}_{t;b}(\underline{\tilde{M}}_b, \underline{\tilde{M}}_b^{inc}) = \\ = \underline{0}\,\forall \underline{\rho} \in S_b \tag{11}$$

When applying the superposition principle and boundary condition (7), (11) can be rewritten as the following magnetic field integral equation with unknown surface current $\underline{\hat{M}}_b$

$$\underline{\hat{H}}_{t;b}(\underline{0}, \underline{\hat{M}}_b) + \underline{\tilde{H}}_{t;b}(\underline{\hat{M}}_b, \underline{0}) = \\ -\underline{\hat{H}}_{t;b}(\underline{\hat{M}}_b^{inc}, \underline{0}) + \underline{\tilde{H}}_{t;b}(\underline{0}, \underline{\tilde{M}}_b^{inc})\,\forall \underline{\rho} \in S_b \tag{12}$$

Coupled magnetic field integral equations

If the coupling between layers includes a large number of modes, numerical problems arise when computing the resulting large S-matrices with sufficient accuracy. In that case it is more efficient to the unknwon currents on both interfaces simulaneously, by a coupled equation.

In this case the boundary condition (8) at both interfaces S_a and S_b can be written in terms of the unknown equivalent surface currents $\underline{\hat{M}}_a$, $\underline{\tilde{M}}_a$, $\underline{\hat{M}}_b$ and $\underline{\tilde{M}}_b$.

$$\underline{\hat{H}}_{t;a} = \underline{\tilde{H}}_{t;a} \Leftrightarrow \underline{\hat{H}}_{t;a}(\underline{\hat{M}}_a^{inc}, \underline{\hat{M}}_a) - \underline{\tilde{H}}_{t;a}(\underline{\tilde{M}}_a, \underline{\hat{M}}_b) = \\ = \underline{0}\,\forall \underline{\rho} \in S_a \tag{13}$$

$$\underline{\hat{H}}_{t;b} = \underline{\tilde{H}}_{t;b} \Leftrightarrow \underline{\hat{H}}_{t;b}(\underline{\tilde{M}}_a, \underline{\hat{M}}_b) - \underline{\tilde{H}}_{t;b}(\underline{\tilde{M}}_b, \underline{\tilde{M}}_b^{inc}) = \\ = \underline{0}\,\forall \underline{\rho} \in S_b \tag{14}$$

When applying the superposition principle and boundary condition (7), (13) and (14) can be rewritten as the following coupled system of magnetic field integral equations with unknown surface currents $\underline{\hat{M}}_a$ and $\underline{\hat{M}}_b$

$$\underline{\hat{H}}_{t;a}(\underline{0}, \underline{\hat{M}}_a) + \underline{\tilde{H}}_{t;a}(\underline{\hat{M}}_a, \underline{0}) - \underline{\hat{H}}_{t;a}(\underline{0}, \underline{\hat{M}}_b) = \\ -\underline{\hat{H}}_{t;a}(\underline{\hat{M}}_a^{inc}, \underline{0})\,\forall \underline{\rho} \in S_a \tag{15}$$

$$-\underline{\hat{H}}_{t;b}(\underline{\hat{M}}_a, \underline{0}) + \underline{\hat{H}}_{t;b}(\underline{0}, \underline{\hat{M}}_b) + \underline{\bar{H}}_{t;b}(\underline{\hat{M}}_b, \underline{0}) = \\ \underline{\tilde{H}}_{t;b}(\underline{0}, \underline{\tilde{M}}_b^{inc})\,\forall \underline{\rho} \in S_b \tag{16}$$

Method of moments

To solve the MFIE we used the method of moments (MoM). The unknown magnetic surface currents $\underline{\hat{M}}_a$ and $\underline{\hat{M}}_b$ are expanded and weighted in terms of Rao-Wilton-Glisson (RWG) basis functions and/or if possible in terms of waveguide mode functions. The unknown currents can be expanded as

$$\underline{\hat{M}}_a(\underline{\rho}) = \sum_m V_m^a \underline{g}_m^a(\underline{\rho}) \\ \underline{\hat{M}}_b(\underline{\rho}) = \sum_m V_n^b \underline{g}_n^b(\underline{\rho}) \tag{17}$$

The weighting can be written in terms of a complex inner product $\left\langle \underline{f}(\underline{\rho}) \middle| \underline{g}(\underline{\rho}) \right\rangle$ (linear in its first term) as

$$\underline{f}(\underline{\rho}) = \underline{0}\,\forall \underline{\rho} \in S_a \rightarrow \left\langle \underline{f}(\underline{\rho}) \middle| \underline{g}_k^a(\underline{\rho}) \right\rangle = 0\,\forall k \\ \underline{f}(\underline{\rho}) = \underline{0}\,\forall \underline{\rho} \in S_b \rightarrow \left\langle \underline{f}(\underline{\rho}) \middle| \underline{g}_l^b(\underline{\rho}) \right\rangle = 0\,\forall l \tag{18}$$

After inseting (17) and application of the weigthing procedure, the two separate MFIE equations (10) and (12) can be written as

$$\sum_m V_m^a \left\langle \underline{\hat{H}}_{t;a}(\underline{0}, \underline{g}_m^a) + \underline{\tilde{H}}_{t;a}(\underline{g}_m^a, \underline{0}) \middle| \underline{g}_k^a \right\rangle = \\ = \left\langle \underline{\tilde{H}}_{t;a}(\underline{0}, \underline{\tilde{M}}_a^{inc}) - \underline{\hat{H}}_{t;a}(\underline{\hat{M}}_a^{inc}, \underline{0}) \middle| \underline{g}_k^a \right\rangle \forall k \tag{19}$$

$$\sum_m V_m^b \left\langle \underline{\hat{H}}_{t;b}(\underline{0}, \underline{g}_n^b) + \underline{\tilde{H}}_{t;b}(\underline{g}_n^b, \underline{0}) \middle| \underline{g}_l^b \right\rangle = \\ = \left\langle \underline{\tilde{H}}_{t;b}(\underline{0}, \underline{\tilde{M}}_b^{inc}) - \underline{\hat{H}}_{t;b}(\underline{\hat{M}}_b^{inc}, \underline{0}) \middle| \underline{g}_l^b \right\rangle \forall l \tag{20}$$

which can be rewritten as two matrix equations

$$A\underline{V}^a = \underline{B} \tag{21}$$

$$C\underline{V}^b = \underline{D} \tag{22}$$

For the *coupled* magnetic field integral equations (15) and (16), this procedure leads to

$$\sum_m V_m^a \left\langle \underline{\hat{H}}_{t;a}(\underline{0}, \underline{g}_m^a) + \underline{\tilde{H}}_{t;a}(\underline{g}_m^a, \underline{0}) \middle| \underline{g}_k^a \right\rangle - \\ -\sum_m V_n^b \left\langle \underline{\tilde{H}}_{t;a}(\underline{0}, \underline{g}_k^a) \middle| g_k^a \right\rangle = \\ = -\left\langle \underline{\tilde{H}}_{t;a}(\underline{\hat{M}}_a^{inc}, \underline{0}) \middle| \underline{g}_k^a \right\rangle \forall k \tag{23}$$

$$-\sum_m V_m^a \left\langle \underline{\hat{H}}_{t;b}(\underline{g}_m^a, \underline{0}) \middle| \underline{g}_l^b \right\rangle +$$
$$\sum_m V_n^b \left\langle \underline{\hat{H}}_{t;b}(\underline{0}, \underline{g}_n^b) + (\underline{\tilde{H}}_{t;b}(\underline{g}_n^b, \underline{0}) \middle| \underline{g}_l^b \right\rangle = \quad (24)$$
$$= \left\langle \underline{\tilde{H}}_{t;b}(0, \underline{\tilde{M}}_b^{inc}) \middle| \underline{g}_l^b \right\rangle \forall l$$

which can be rewritten as the one single matrix equation

$$\begin{bmatrix} A+B & C \\ D & E+F \end{bmatrix} \begin{bmatrix} \underline{V}^a \\ \underline{V}^b \end{bmatrix} = \begin{bmatrix} \underline{G} \\ \underline{H} \end{bmatrix} \quad (25)$$

Spectral green's function

To solve equations (21-22) (or (25) for the coupled system) one must still determine the matrices A and C and vectors B and D. These terms include the magnetic field that is generated by a source, in a region near the source, and/or in a source-free region. These terms can be found from the Green function of the stratified problem.

In a waveguide the transverse electromagnetic field can be written as

$$\underline{E}_t(\underline{\rho}, z) = \sum_{\alpha,m} V_m^a(z) \underline{e}_m^\alpha(\underline{\rho})$$
$$\underline{H}_t(\underline{\rho}, z) = \sum_{\alpha,m} I_m^a(z) \underline{h}_m^\alpha(\underline{\rho}) \quad (26)$$

where α represents the polarization index and m represents the waveguide mode index. In layered space the transverse electromagnetic field can be written as

$$\underline{E}_t(\underline{\rho}, z) = \sum_\alpha \int d\underline{k}_t \cdot V^a(\underline{k}_t, z) \underline{e}_m^\alpha(\underline{\rho})$$
$$\underline{H}_t(\underline{\rho}, z) = \sum_\alpha \int d\underline{k}_t \cdot I^a(\underline{k}_t, z) \underline{h}^\alpha(\underline{\rho}) \quad (27)$$

where α represents the polarization index and $\underline{k}_t$ represents the transverse wavevector. Note that the index m in the waveguide formulation and the vector $\underline{k}_t$ in the layered space formulation have a similar meaning. Two types of polarization exist. For transverse magnetic (TM) polarization, indicated by $\alpha = '$, the transverse wavevectors $\underline{e}'(\underline{\rho})$ and $h'(\underline{\rho})$ can be written as

$$\underline{e}'(\underline{\rho}) = \frac{\underline{\nabla}_t \Phi(\underline{\rho})}{\underline{k}'_t} \qquad \underline{h}'(\underline{\rho}) = \frac{\underline{\nabla}_t \Phi(\underline{\rho})}{\underline{k}'_t} \times \hat{z} \quad (28)$$

where $\Phi(\underline{\rho})$ satisfies

$$[\nabla_t^2 + k'^2_t]\, \Phi(\underline{\rho}) = 0 \,\forall \underline{\rho} \in S$$
$$\langle \Phi(\underline{\rho}) | \phi(\underline{\rho}) \rangle = \text{orthonormal} \quad (29)$$

supplemented with proper boundary conditions. For transverse electric (TE) polarization, indicated by $\alpha = ''$, the transverse wavevectors $\underline{e}''(\underline{\rho})$ and $h''(\underline{\rho})$ can be written as

$$\underline{e}''(\underline{\rho}) = \hat{z} \times \frac{\underline{\nabla}_t \Psi(\underline{\rho})}{\underline{k}''_t} \qquad \underline{h}''(\underline{\rho}) = \frac{\underline{\nabla}_t \Psi(\underline{\rho})}{\underline{k}''_t} \times \hat{z} \quad (30)$$

where $\Psi(\underline{\rho})$ satisfies

$$[\nabla_t^2 + k''^2_t]\, \Psi(\underline{\rho}) = 0 \,\forall \underline{\rho} \in S$$
$$\langle \Psi(\underline{\rho}) | \psi(\underline{\rho}) \rangle = \text{orthonormal} \quad (31)$$

supplemented with proper boundary conditions. For the waveguide, the transverse wavevectors depend on the shape of the aperture, i.e. depend on the proper boundary conditions for solving (29) and (31).

For the *layered space*, the transverse wavevectors can be written in a similar form.

$$\Phi(\underline{k}_t, \underline{\rho}) = \frac{1}{2\pi} e^{-j\underline{k}_t \bullet \underline{\rho}} \qquad \underline{e}'(\underline{k}_t, \underline{\rho}) = \frac{j}{2\pi} \hat{k}_t e^{-j\underline{k}_t \bullet \underline{\rho}}$$
$$\underline{h}'(\underline{k}_t, \underline{\rho}) = -\frac{j}{2\pi} \hat{\alpha}_t e^{-j\underline{k}_t \bullet \underline{\rho}} \qquad \hat{k}_t = \underline{k}_t / \left\| \underline{k}_t \right\| \quad (32)$$

$$\Psi(\underline{k}_t, \underline{\rho}) = \frac{1}{2\pi} e^{-j\underline{k}_t \bullet \underline{\rho}} \qquad \underline{e}''(\underline{k}_t, \underline{\rho}) = \frac{j}{2\pi} \hat{\alpha}_t e^{-j\underline{k}_t \bullet \underline{\rho}}$$
$$\underline{h}''(\underline{k}_t, \underline{\rho}) = \frac{j}{2\pi} \hat{k}_t e^{-j\underline{k}_t \bullet \underline{\rho}} \qquad \hat{\alpha} = \hat{k}_t \times \hat{z} \quad (33)$$

When combining (27) with (32) and (33), the spectral representation of the transverse electromagnetic field is recognised.

The longitudinal components $V^a(z)$ and $I^a(z)$ satisfy the so-called transmission line equations

$$-\partial_z V^a(z) = jk_z^\alpha Z_\infty^\alpha I^a(z) + v^a(z)$$
$$v^a(z) = \langle \underline{J}_{mt}^{eff}(\underline{\rho}, z) \times \hat{z} | \underline{e}^\alpha(\underline{\rho}) \rangle \quad (34)$$

$$-\partial_z I^a(z) = jk_z^\alpha Y_\infty^\alpha V^a(z) + i^a(z)$$
$$i^a(z) = \langle \hat{z} \times \underline{J}_{et}^{eff}(\underline{\rho}, z) | \underline{h}^\alpha(\underline{\rho}) \rangle \quad (35)$$

At sourcefree continuous sections, the longitudinal components $V^a(z)$and $I^a(z)$ satisfy

$$[\partial_z^2 + k_z^{\alpha^2}] V^a(z) = 0 \qquad I^a(z) = j \frac{Y_\infty^\alpha}{k_z^\alpha} \partial_z V^a(z) \quad (36)$$

$$[\partial_z^2 + k_z^{\alpha^2}] I^a(z) = 0 \qquad V^a(z) = j \frac{Z_\infty^\alpha}{k_z^\alpha} \partial_z I^a(z) \quad (37)$$

At discontinuous boundaries $z = z_m$ the following boundary conditions hold for $V^a(z)$ and $I^a(z)$

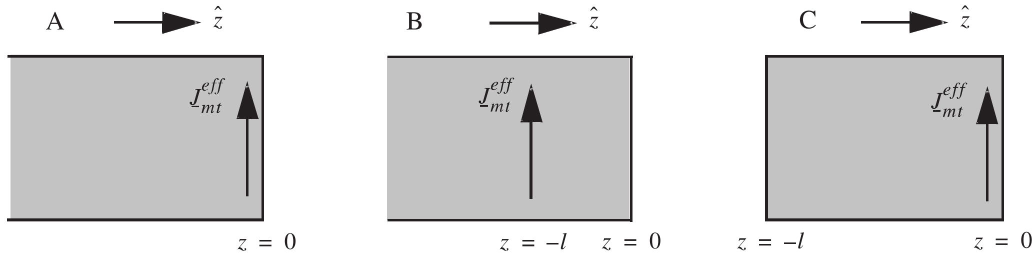


Figure 3: Examples Longitudinal Field Problems

$$\lim_{\Delta z\to 0} I^a(z_m-\Delta z)-V^a(z_m+\Delta z)= = \lim_{\Delta z\to 0}\int_{(z_m-\Delta z)}^{(z_m+\Delta z)} v^a(z)\mathrm{d}z \tag{38}$$

$$\lim_{\Delta z\to 0} I^a(z_m-\Delta z)-I^a(z_m+\Delta z)= = \lim_{\Delta z\to 0}\int_{(z_m-\Delta z)}^{(z_m+\Delta z)} i^a(z)\mathrm{d}z \tag{39}$$

All of these equations are derived from Maxwell's equations by separating the transverse from the longitudinal field components (Marcuvitz-Schwinger equations). The longitudinal field problem is the same for the waveguide as well as for the layered space, whereas the transverse field problem differs in the supplemented boundary conditions.

Three examples will be given for which the longitudinal field problem $I^a(z)$ is solved (see Fig. 3). These solutions are used for both the waveguide $I^a_m(z)$ as well as for the layered space $I^a(\underline{k}_t, z)$.

Example A : We consider a half-infinite length waveguide closed at $z = 0$ with a metal wall. A magnetic current $\underline{J}^{eff}_{mt}$ is positioned close to this metal wall at $z = 0$.

$$I^a(z)=-Y^\alpha_\infty \langle \underline{J}^{eff}_{mt} \,|\, \underline{h}^\alpha\rangle e^{jk^\alpha_z z} \forall z<0 \tag{40}$$

Example B : We consider a half-infinite length waveguide closed at $z = 0$ with a metal wall. A magnetic current $\underline{J}^{eff}_{mt}$ is positioned at $z = -l$ at a distance l from this metal wall at $z = 0$.

$$I^a(z)=\begin{cases} -Y^\alpha_\infty \langle \underline{J}^{eff}_{mt} \,|\, \underline{h}^\alpha\rangle \cos(k^a_z l) e^{jk^\alpha_z z} \forall z<-l \\ -Y^\alpha_\infty \langle \underline{J}^{eff}_{mt} \,|\, \underline{h}^\alpha\rangle \cos(k^a_z z) e^{-jk^\alpha_z l} \forall -l<z<0 \end{cases} \tag{41}$$

Example C : We consider a finite length waveguide of length l closed at both sides with metal walls at $z = -l$ and $z = 0$. A magnetic current $\underline{J}^{eff}_{mt}$ is positioned at $z = 0$ close to the right metal wall.

$$I^a(z)= jY^\alpha_\infty \langle \underline{J}^{eff}_{mt} \,|\, \underline{h}^\alpha\rangle \frac{\cos(k^\alpha_z z)}{\sin(k^\alpha_z l)} \forall -l<z<0 \tag{42}$$

Using periodicity

The interface S_b is closed with metal, making the outer side at $z = d$ (see Fig. 2) the only place for the the unit cells to interact with eachother in this equivalent formulation. So this is the place to take into account the periodic character of the structure. We do this by making the unknown current $\underline{\tilde{M}}_b$ periodic in behaviour, i.e. we replace $\underline{\tilde{M}}_b$ with $\underline{\tilde{M}}^{per}_b$ in the magnetic field density $\underline{\tilde{H}}_{t,b}(\underline{\tilde{M}}_b, \underline{0})$. Since $\underline{\tilde{M}}_b = -\underline{M}_b$, the periodic expansion function for the outer side of this interface can now be written as

$$\underline{\tilde{M}}^{per}_b(\underline{\rho})=-\sum_n V^b_n \underline{g}^{b;per}_n(\underline{\rho}) \tag{43}$$

The periodic expansion function $\underline{g}^{b;per}_n$ is formulated as a function of the non-periodic expansion function $\underline{g}^b_n$ as

$$\underline{g}^{b;per}_n(\underline{\rho})=e^{-j\underline{k}^j_t\bullet\underline{\rho}}\left[\left(\underline{g}^b_n(\underline{\rho})e^{j\underline{k}^j_t\bullet\underline{\rho}}\right)*\Pi_{\underline{d}_1,\underline{d}_2}(\underline{\rho})\right] \tag{44}$$

where * denotes convolution with respect to $\underline{\rho}$ and where $\Pi_{\underline{d}_1,\underline{d}_2}$ denotes the so-called Dirac brush function defined by

$$\Pi_{\underline{d}_1,\underline{d}_2}(\underline{\rho})=\sum_{m_1,m_2=-\infty}^{\infty}\delta(\underline{\rho}-m_1\underline{d}_1-m_2\underline{d}_2) \tag{45}$$

the spectral representation of the periodic expansion function $\underline{g}^{b;per}_n$ can be expressed as

$$\langle \underline{g}^{b;per}_n \,|\, h^\alpha\rangle(\underline{k}_t)=\frac{4\pi^2}{A}\Pi_{\underline{k}_1,\underline{k}_2}(\underline{k}_t-\underline{k}^i_t)\langle \underline{g}^b_n \,|\, \underline{h}^\alpha\rangle(\underline{k}_t) \tag{46}$$

where k_1 and k_2 denote the reciprocal basis vectors (Floquet grid) defined by

$$\underline{k}_1 = \frac{2\pi\underline{d}_2\times\hat{z}}{\underline{d}_1\times\underline{d}_2\bullet\hat{z}} \qquad \underline{k}_2 = \frac{2\pi\hat{\underline{z}}\times\underline{d}_1}{\underline{d}_1\times\underline{d}_2\bullet\hat{z}} \tag{47}$$

$$\underline{k}_1\bullet\underline{d}_j = 2\pi\delta_{i,j}$$

Innerproducts

In the method of moment formulation the following four types of innerproducts appear:

- "Waveguide mode" current expansion with "waveguide mode" field expansion,
- "Rao-Wilton-Glisson" current expansion with "waveguide mode" field expansion,
- "Waveguide mode" current expansion with "Floquet mode" field expansion,
- "Rao-Wilton-Glisson" current expansion with "Floquet mode" field expansion.

These innerproducts have been formulated in a closed form.

Validation

The two models are validated by comparing the results with those generated by a commercial simulation package HFSS. Our first model described in this paper is represented by the separate MFIEs (21) and (22). These two equations are solved numerically and the results are then cascaded to obtain the behaviour of the total structure. Our second model described in this paper is represented by the coupled MFIE (25). This equation is solved numerically.

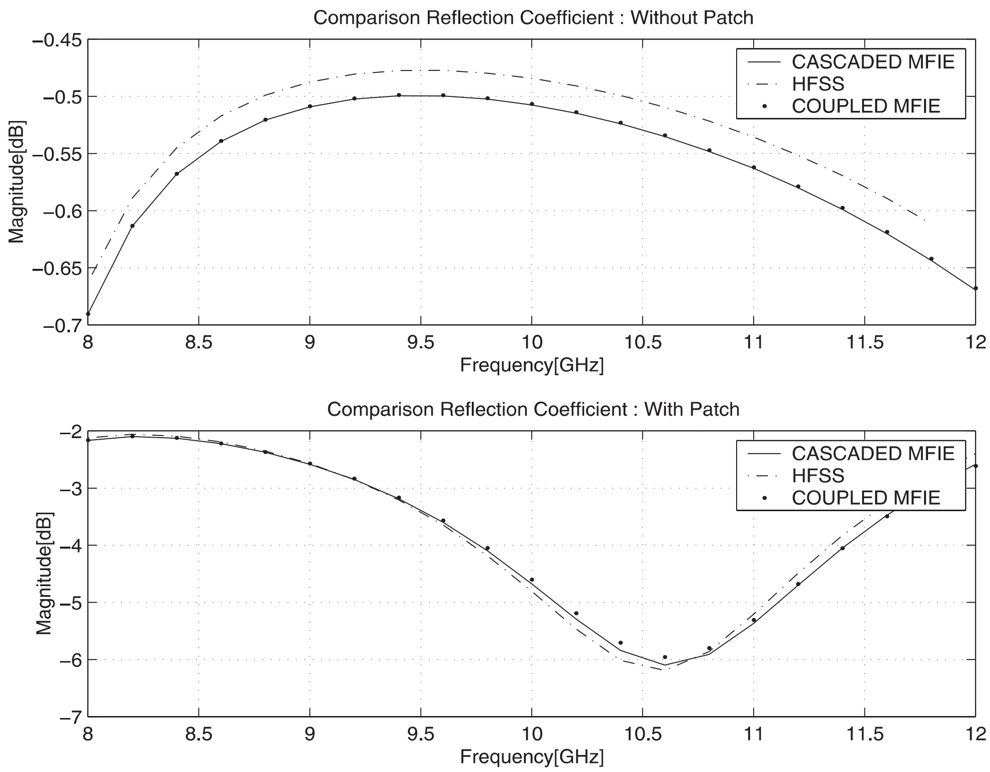
The total structure has been simulated with and without the patch. the interfaces S_a and S_b (see Fig. 2) are meshed in terms of Rao-Wilton-Glisson expansion functions. In the slot an incident fundamental waveguide mode is used to excite the structure. The broadside incident wave situation is considered. The frequency band of interest is set to be I/J-band. The reflection coefficient of the fundamental waveguide mode in the slot is calculated.

The results of our two models and of HFSS is plotted in Fig. 4. The upper subplot in this figure represents the simulation of the structure without the patch whereas the lower subplot represents the simulation with the patch. We can see that in both situations there is a very close agreement between our models and HFSS. We can also see that the patch gives the total structure better transmission properties.

Conclusions

In this paper we have considered the analysis of stratified periodic electromagnetic field problems. These type of problems involve structures that can contain both waveguide as well as periodic layered space components. A ge neral theory is presented where these waveguide and periodic layered space components are treated equally.

Figure 4: Simulation Results : Cascaded MFIE, Coupled MFIE and HFSS



Two numerical models have been developed for the analysis of stratified periodic electromagnetic field problems. The first model cascades the results of two numerically solved magnetic field integral equations. The second model numerically solves a coupled system of two magnetic field integral equations.
These two models are used to calculate the reflection behaviour of an arbitrary feed-radiator-frequency selective surface structure. The results of these two models are benchmarked against eachother and against available commercial tooling such as HFSS. A very close agreement has been obtained between all three models.

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Focal Fields in Reflector Antennas and Associated Array Feed Synthesis for High Efficiency Multi-Beam Performances

M. Ivashina and C.G.M. van 't Klooster

Abstract

The paper describes status results of investigations into focal-field distributions in reflector antennas with a symmetrical and with an off-set geometry. For the symmetrical case, the 25-m radio-telescope antenna as included in the Westerbork synthesis array [1] has been considered. For the offset geometry, a working scenario has been taken comparable to the Large Deployable Antenna (LDA) as currently being realised by Alenia [2]. Grid configurations are proposed for the focal plane arrays, which -when properly excited - provide high efficient beam patterns. This is important for off-axis beams, for which the focal field distributions are deformed. The approach to investigate array-fed reflector antennas 'the other way around' as compared to the usual adopted synthesis of reflector antennas, gives an insight into the actual field distributions in the focal region for reflector antennas as considered here, namely a front-fed and an offset geometry. This is well applicable for varies type of dual reflector antennas. It supports the understanding of sizing and allocating the excitations of the set of active array elements. Together with a coupling theorem, derived from Maxwell's equations (reciprocity related, known under different names like Lorentz-reciprocity theorem or Robieux,, etc) one can arrive at a suitable focal plane array configuration, which performs optimum. A status of the ongoing work is presented.

Introduction

The common practice in realization of desired reflector antenna patterns and study of the latter is to synthesize the radiation pattern or the illumination patterns of the reflector aperture, using one or another synthesis tool and so to get high efficient radiation (in transmission mode) patterns. Assuming reciprocity, it is also valid for the receive situation. In a receiving situation the antenna system (reflector *with* the feed-system) transforms the incoming plane wave from free space into a guided wave in the feed-system. Then, the receiving feed – located in the focal region - should be able to intercept as much as possible the power, which is concentrated in a focal region of the reflector. The feed system is supposed to compensate also the field distortions, which appear after reflection from the curved reflector, in particular when the direction of observation is 'off' from the bore-sight direction. Hence, feed system synthesis can be seen differently as to solve problems of an optimum illumination for reflector antennas or an accurate field imaging of the source (incoming field distribution) in the observation region.

Present-day applications of the reflector antennas such as, for example for satellite-telecommunication, as well as radioastronomical antenna systems, require operation with not only a single-beam feed, but also large number of independent antenna beams. Furthermore, such beams can be contoured, thus not necessarily like a pencil-beam. To support a multibeam performance with the reflector antennas, the feed array can be realised with horn-, waveguide- or microstrip-array systems. Additional advantages of array feeds are related to a use of multi-element clusters out of available feed array system to synthesize off-axis patterns or complex "contour beam" patterns for the optimum radiation performances.

Here, we study only a prime -focus and an off-set parabolic reflector configuration to demonstrate capabilities and limitations of both reflector geometries in terms of multi-beam and scanning performances. As an example for the reflector configuration we have considered the 25-meter prime-focus radio telescope antenna of Westerbork (a symmetrical parabolic reflector with an F/D of 0.35 [1]) and offset reflector geometry with 6.3 m focal distance and a projected aperture of 12 m. (It compares to the Large Deployable Antenna [2] as considered by Alenia). Extension of the approach for other type of dual reflector systems (shaped or non shaped) might be understandable.

Antenna requirements

Reflector antennas are used in rather different scenarios with accordingly different requirements as needed. Antenna efficiency is of high importance, combined with radiation pattern 'cleanliness' or sidelobe performances and beamoverlap at prescribed levels. Each of the 14 Westerbork prime-focus 25-meter reflector antenna supports as array element in an array of 14 radio telescopes the observation in a receiving operation mode.

The offset reflector antenna (like the Large Deployable Antenna or LDA) on a satellite can be used for different telecommunication applications such as broadcasting and multicasting services or for Earth observation tasks, for multiple or contoured beams. Here we limit the generalized discussion to cluster feed considerations for reflector antennas to handle multi-beam performance with prescribed requirements for antenna efficiency. Our interest is concerning aspects related to main requirements to be evaluated like:

- Efficient Multi-beam performance: Maximal coverage of a field of view according to a scenario with power losses less than 50%. This implies also an isolation of the beams or an overlap at a level of < 3dB.
- Optimal illumination pattern beam: Maximal gain of the reflector aperture with spillover losses < –12 dB, preferably also for of-axis beams.

Problem formulation

The field of view (FOV) of reflector antennas is limited by distortions of antenna radiation beams, which appear when scanning off-axis. It is possible to reduce the effect of such distortions by using an array feed located in the vicinity of the focus. Then the elements need to have such excitations that the produced field distribution can produce the necessary aperture phase and amplitude setting such as to compensate the actual focal field distribution as needed.

Different techniques have been used to obtain the necessary array excitation matrix [3]. The conjugate field-matching method (CFM), based on focal field analysis, gives the array excitation matrix as the conjugate of the focal field produced by incident plane wave when the antenna operated in the receiving mode. Using reciprocity considerations, the actual field distribution produced by the feed array can be optimized to give the necessary excitations. (Based on the reciprocity theorem, the field produced by a single feed element can be conjugated to give its corresponding excitation, as needed, this obviously in the feed-array environment with mutual coupling included).

Focal field distribution analysis

Before the appropriate array feed excitation coefficients will be determined, the Focal Field Distribution (FFD) in the focus region should be reconstructed for each off-axis incident direction using an incoming plane wave. The FFD can be estimated by illuminating the reflector with a plane wave and then derive field in the focal region using PO/PTD or GO/GTD techniques [3].

This approach has been used in this paper and a professional antenna design program GRASP8-SE [4] has been applied for calculation of the focal field distributions.

Distribution of fields in the focal region - Westerbork

The properties of point source images (represented by an incoming plane wave) by the Westerbork reflector have been investigated for scan directions corresponding to the Field Of View (FOV) arranged by several radiation patterns overlapping at –3 dB. Figure 1A) shows the 2D distribution of the multi-beam focal field in the plane f = 0 deg at the frequency of 3.5GHz for a space domain bound by a 5λ by 5λ (5l × 5l pixels) frame. We plotted the contour curves only for –3dB and –12 dB levels. The analysis shows us that at the given region it is possible to form one central beam and six off-axis beams, which allow the maximal angular size of the FOV of 1.7 deg (for positive theta, as measured from the bore-sight direction). The focal field of an off-axis incoming plane wave is distorted due to the appearance of phase and amplitude distortions, which contribute differently depending on the distance expressed in beam diameters (maximum contribution is as shown for the 7th beam). As Westerbork is 'world-famous' as very accurate polarimeter, the treatment of polarization for the off-axis beams deserves dedicated attention (to be further investigated).

Let us estimate the scanning performance for the Westerbork reflector. The focal field distribution

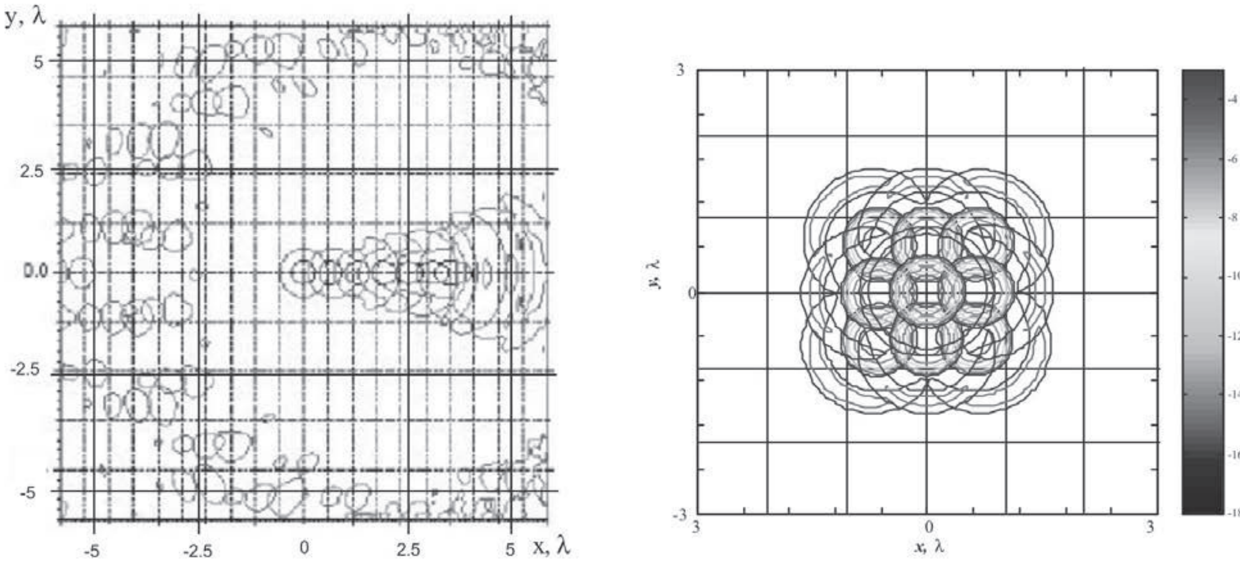


Figure 1A (left) and 1B (right)
Fig.1A shows focal plane distributions for different plane wave incidence situations for the 25 m front-fed symmetrical parabolic antenna, which is used in the Westerbork synthesis array (consisting out of 14 of such 25-meter antennas). Fig. 1B shows the focal field distributions for a situation with 9 beams out of such 25-m (f/D = 0.35) antenna.

for an axial incident plane wave (the central contour beam) is represented by a group of ideal circular rings. For this case, all power reflected from the dish surface can be intercepted by a feed, which is located in the focus. For an off-axis incident plane wave relating to the second overlapped beam in the far field we have the off focus peak and deformed contours of the respective levels for the focal field distribution (rings of the contour beam in the focal plane). The power, which is concentrated into the region bounded by the rings, cannot be captured by a classical horn feed because the image exceeds the feed size and has a complex form. In addition one side lobe occurs for the next beams due to (coma) aberrations in the directions of scanning plane. This leads to essential power losses.

Thus, to intercept the focal image of an (out) 'off'-axis incoming plane wave or an off-axis source distribution (source) it is necessary to use a feed-array with enough elements to capture not only the power concentrated in the main beam but also in the side lobes of the focal plane distribution surrounding the main lobe in the focal plane. Such a task becomes rather difficult for the outer beams especially for the sixth and seventh main-lobe in the focal plane, because for these lobes we have already side lobes also at the opposite side of the main lobe of the focal field in the considered domain. One can observe this at the negative axis as shown in Fig.1A.

Vicinity of focus - where to intercept the field distribution in the focal region

To obtain full information about the structure of such imaging we studied the field distribution not only in the geometrical focal plane but also in the neighborhood of this plane along the symmetry-axis of the parabola. Knowing the 3D Focal Field Distributions (FFD) near the focus is of particular importance for the procedure of the field matching. It allows defining the region (plane/surface) for the most efficient matching (where distortions are minimal). Fig 2 shows the amplitude and phase field distributions in the vicinity of the focus of the prime focus reflector for three different cases: an XY plane at Z = 0 (focus point), at Z = 0.5 and at Z = – 0.5 λ.

The dependence has been computed for the central beam and the first off-axis beam spots at (φ = 0 deg and (φ = 45 deg, but here only the central beam is presented. The results show that when moving off focus along the focal axis ('towards' or 'away from' the reflector along the feed axis Z), the sizes of the image rings increase, the diffraction minimums disappear, and the amplitude field distribution becomes more extended.

Also polarization information is obtained. For the situation associated with an incoming plane wave in the diagonal plane the effects are accompanied by splitting the side lobes in the focal plane. The plane for the most efficient matching of the fields, reflected from the dish and produced by the array

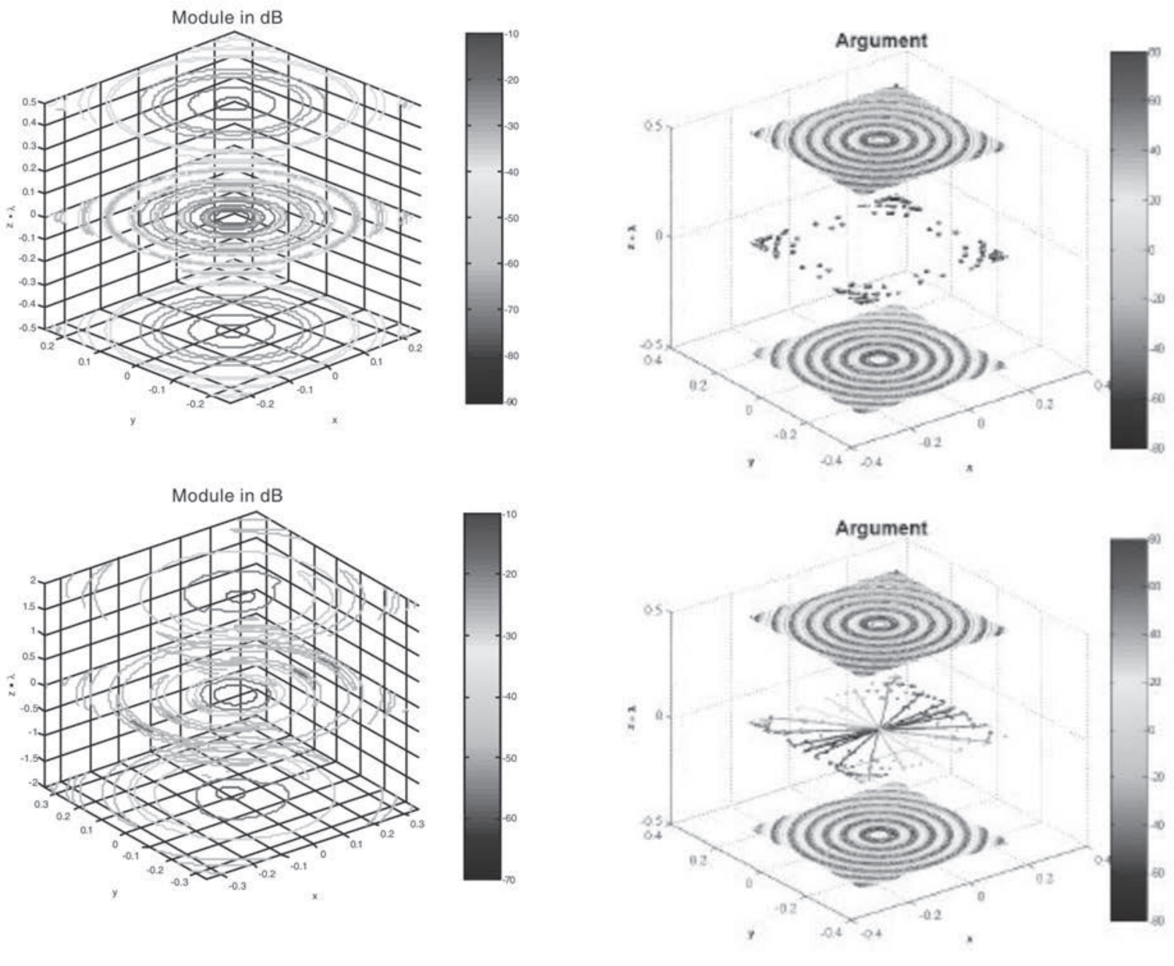


Figure 2: Focal field distributions near the focus, for a symmetrical reflector antenna (f/D = 0.35) on top and (bottom) for an offset reflector antenna (12m aperture, f = 6.3 m, subtended angle ~2 35.6°)*

feed is the geometrical focal plane. To perform the field matching even not far from the focal plane the array feed design should be larger and have more elements to capture the same power as those for matching procedure in the focal plane.

Actually the surface for best matching might be slightly curved as is anticipated in relation to the so-called Petzval surface, on which feed elements should be located in order to produce relatively the best pattern, when off-focus in a parabolic reflector. We however calculated the field distributions in rectangular planar grids.

Efficient multi-beam performance

According to the simulation results shown in Fig.1A it is possible to cover the central Airy disk for a 25-m Westerbork parabolic reflector with 0.35 F/D by a single feed with a size 1.2 λ,. We could then design a grid of the array feed that would accommodate 9 feeds (for one central and 1st overlapped off-axis pattern beams), thus providing a multi-beam performance with power losses less than 50%, according to the scenario (See Fig 1B). Here, it is of importance to estimate not only the size of the array, but also a minimum number of elements and possible spacing of the array grid, so that it can handle the highest and a lowest frequency of the desired bandwidth.

Offset reflector geo metry

A similar approach has been followed for the investigation of the focal field distribution in an offset parabolic reflector antenna. The geometry considered is as in [2] ($D_{\text{projected aperture}}$ = 12m, focal distance f = 6.3 m). Interesting aspects associated with a systematic behavior of the offset reflector are observed in the focal field distributions (Fig. 2 bottom). The possibility to compensate beam distortions for a multi-beam situation with sub-arrays (grouping of elements) from a hexagonal focal plane array feed is explored in this section.

We have investigated for a number of incoming plane waves the related focal field distribution near to locations, which correspond almost to sample

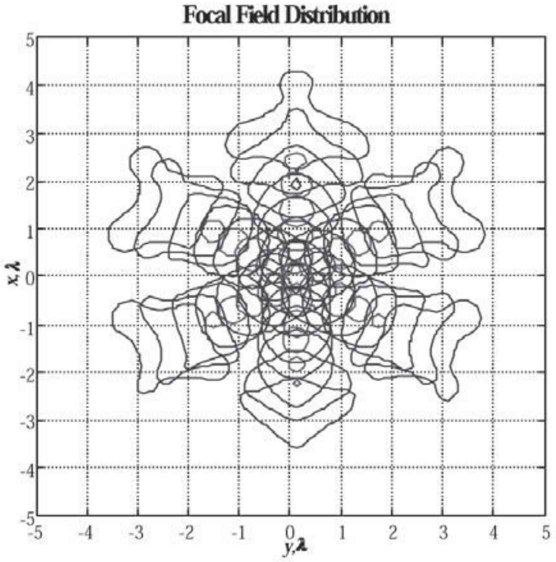


Figure 3A: Focal field distributions (incoming plane waves incoming from directions in planes 60° separated).

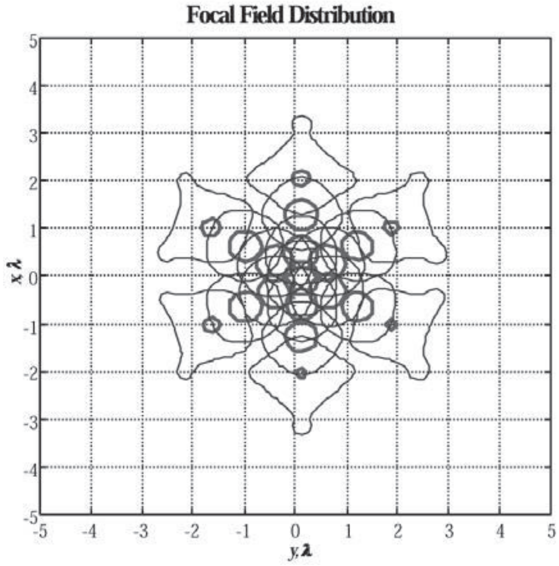


Figure 3B: Focal field distributions (incoming plane waves incoming from directions in planes 60° separated). Note the triangular and trapezoidal distortions for the different beams.

points at a single feed-horn location. In this way a number of focal field distributions was derived as shown in fig. 3A and 3B. Only distributions along directions corresponding to the symmetry lines in the hexagonal array are shown, resulting therefore in a star-like picture with 6 sets of focal plane distributions. The off-set geometry of the reflector causes deformation of the separate focal field distributions and it is very interesting to observe the deviating distortion, when going off from the focus in the lateral direction in the focal plane.

Thus, for the first and second off-axis beams we have square contours of the focal field distributions. For the next incident directions the properties of the focal field images are with the following observations: along the plane of symmetry of the reflector the focal beam spot is characterized by triangular shapes with 3 shoulder or side-lobe peaks. The values are growing for the far-out beams. In other directions, where the curvature of the reflector is also bigger than for the on-axis direction, the number of side-peaks of the beam image is 4 and the contours are trapezoidal as it is observable in Fig. 3A and Fig. 3B. This shows the importance of a necessity to have the appropriate beam-forming network.

These results indicate - as everybody can see - that the sampling of the focal field, - if carried out with a hexagonal array - should be handled with care. Off-axis beams would require more than 3 and 4 (for close and far beams) feedelements with square, triangle or trapezoidal grid configurations to reconstruct an optimum high-efficient antenna pattern.

As a logical consequence, the hexagonal field sampling must be handled with care. A feed-network with three Butlermatrix networks may not provide optimum radiation patterns, because of the differences in number of feed elements needed for the optimu m radiation patterns when off-axis. It is for such situation, that there is a necessity to investigate in more detail, how the feed-network should be realized with *dedicated* grouping of elements.

Illumination patterns with improved efficiency and array feed configuration

The efficiency of single parabolic reflector antennas is mainly determined by the capability of the feed to produce a desirable field distribution on the reflector aperture. Such a distribution is considered to be optimal when maximal G/T ratio and minimal spillover losses are achieved. The radiation pattern of an ideal feed should therefore have a secantsquared form with a cut-off at the rim of the dish. The cut-off values should be sharp and occur at the largest as possible distance from the center of the aperture.

For the reflector antennas under consideration the ideal pattern cut-off, being assumed of –12 dB level here, will occurs for the direction close to 36.5 deg and 71 deg respectively for the off-set and axis -symmetric parabolic reflector antenna. Additio-

nally to this, we found that in the axial direction the prime focus 25-m reflector should be illuminated 3dB lower relatively to the peak, while for the offset parabolic reflector considered here, with a larger F/D a pattern with a dip of 0.8 dB gives near to uniform illumination. Taking into account its small value, later on, we will neglect the criterion in a course of the feed pattern optimization for the offset configuration.
A high efficiency with a single beam illumination pattern can be realized by using a feed like a corrugated horn or a coaxial waveguide for the respective reflector antennas [5]. These feeds can operate using a certain combination of several radiating modes and so provide the required shape of the reflector illumination pattern with a low spillover level and a rather large pattern width. Depending on the number of necessary modes which could be described as well with a corresponding number of radiating rings the overall dimensions of the total radiating apertures of the feed can be from one to several wavelengths and it becomes even larger, if a wider frequency band has to be considered (as is usual a situation of interest in radio-astronomy) [6]. However, the use of corrugated horns and coaxial waveguides as 'multibeaming' feeds presents some difficulties to handle efficient scanning of the beam due to the spacing between the separate elements in an eventual feed array. The consequence is also a lower level of the overlapping point in the patterns within the FOV for the different feed elements. Moreover, the desired excitation for off-axis beams differs very much from what can be realised with such multi-mode element, with as a consequence a reduced efficiency. In particular, for large F/D reflectors the spacing should be preferably less than 1λ and for F/D < 0.4 less than about 0.5λ [7]. This can also be explained with sampling criteria (Kotelnikov-Nyquist) for the focal field distribution, when appropriate overlap points in patterns are needed.

Taking into account the requirements to the power losses less than 50% with isolation or the overlapping level < 3dB the single feed cannot be used per beam and it is necessary to design an array feed. In the paper we consider array antennas consisting of horns with typical aperture size between 0.75λ to 1λ (for LDA with F/D = 0.525) and integrated arrays with even narrower spacing for the Westerbork reflector with F/D = 0.35. They are considered for a single- and multi-beam scenario.

An array configuration has been realized for the Westerbork 25 meter reflector antenna on the basis of 8 × 9 Vivaldyelement array antenna with 2.7 cm spacing [8]. The rectangular grid array supports a field sampling with spacing between 0.2λ to 0.6λ for the 2.2-7 GHz range. The number of the active elements was selected from 12 to 25 for different constructions with an overall dimension of the active zone of the array feed corresponding to 1.2λ. In the course of the work the Vivaldy array-feed has been investigated over a band of 2-5 GHz and compared with the 13 cm coaxial horn feed currently used for the 25m 0.35F/D telescope in Westerbork [8].

The model of the array feed has been developed on a principle of excitations grouping in radiating concentric rings of array elements and has some similarity to the situation as used in a coaxial horn. As a result, the constructions of the dense array antennas consisting of two radiating rings have been proposed. For a selected frequency of 3.5 GHz, the optimum radiation patterns have been obtained for the following excitation coefficients of (-3dB, 180 deg) and (-10dB, 90 deg) for inner and outer rings correspondingly (see Fig. 4 A)). It should be mentioned that this excitation set is valid for a limited frequency band (about 30 %) because of the frequency dependence of the lateral size of the focal field distribution. The aspect of sizing the groupings and the frequency dependence will be further investigated.
A feed - array antenna consisting of concentric rings allowed to obtain an illumination pattern, which is close to a required secant-squared form with –18 dB level at the rim of the reflector and –3dB in the axial direction. In practice another outer ring of passive elements should be added to decrease scattering effects (dummy elements). Then, a singlebeam array feed for high efficiency will have 7 × 7 elements.

For the LDA reflector antenna model of the single array feed has been developed on the basis of a hexagonal array of horn elements with a tri-angular grid (Fig. 4 C). One of the working assumptions has been made, that the array consists of short horn-like elements with λ-spacing, with an element field pattern approximated with a Gaussian beam. The subtended angular interval was assumed to be ± 36.5 deg for the offset antenna and the frequency band considered to be 2-2.7 GHz. A grouping of 3, respectively 5-horns, 7-horn groups out of the

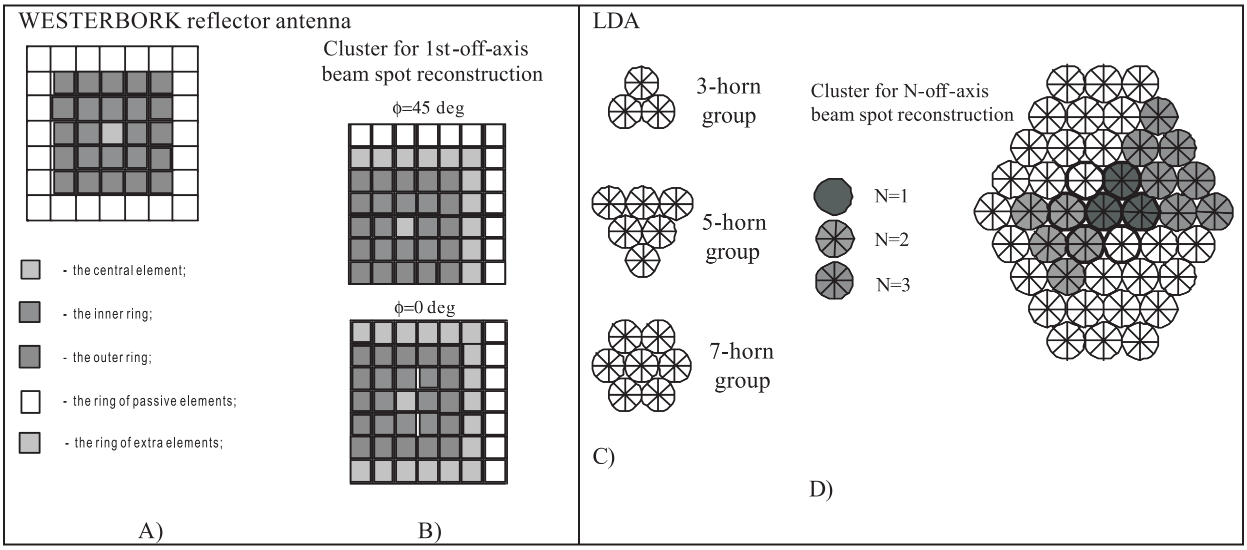


Figure 4: Models for different array feed configurations for a single- and multi-beam performance.

hexagonal array has been investigated and for the assumed feed-element sizing an edge illumination resulted of less than –12 dB for the best pattern for different azimuth directions φ in the feed coordinate system at the rim of the reflector, relative to 0dB in the axial direction. In this way patterns have been obtained using groupings of 3, 5 and 7 elements (Fig. 4 C).

For the central beam (on-axis pattern) a central and 6 surrounding elements in the hexagonal array have been considered as grouping. An optimum excitation for this grouping followed with the 6 elements at –8 dB compared to the central element. For a grouping of three elements an equal power sharing was considered, to achieve minimal spillover illumination –12 dB. The optimization work is currently ongoing. It is possible to find the excitation coefficients for various sub-groupings (carefully determined in sizing) such as to optimize the pattern performances also for off-axis beams. As indicated in fig.6 this is in progress.

Efficient multi-beam performance

Results obtained earlier from the transmitting and receiving operation points of view allow us to develop the generalized recommendations for the multi-beam array feed performance. We present two designs of the array feeds for the reflector antennas under consideration and their radiation patterns for the prescribed requirements according to the scenarios.

For the prime -focus reflector systems, the array-feed cluster should have a size not less than focal beam spots and the configuration of elliptical or dumbbell shaped radiating rings according to the structure of the focal field. Practically it is realized by means of the circular or rectangular grids (see example Fig. 4A and 4B) with sufficient density of the array elements for an accurate sampling of the field. (Larger in extent too handle off-axis beams). The excitation system has to be matched with conjugate focal fields of the incident plane wave when antenna operated in a receiving mode and to provide the optimal shape of the efficient illumination pattern of the reflector aperture. It is reminded, that the size of the focal field distributions is very frequency dependent, while a focal-feed array geometry is fixed. Thus an optimisation should be carried out not only for the different off-axis beams, but also for different frequencies, when the bandwidth of interest is wide (see also [8]).

For the offset reflector antennas the desired grid configuration of the clusters will depend not only on the ‘off-axis’ value of the direction of the incidence, but also on the azimuth direction (due to the lack of rotation symmetry in the offset configuration). It means that the elements of the array feed should be combined in clusters of different configurations such as triangular along the plane of symmetry of the reflector and square, trapezoid in other directions.

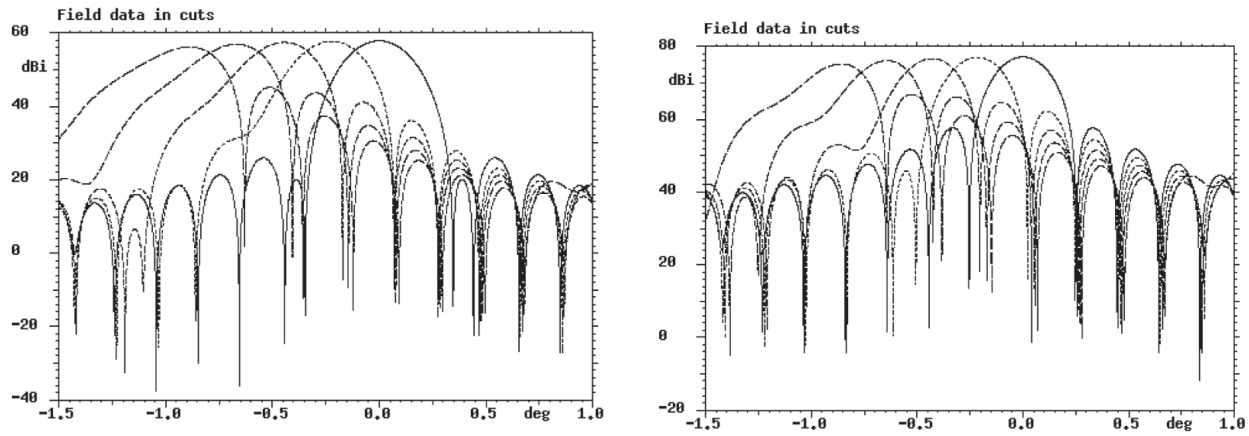


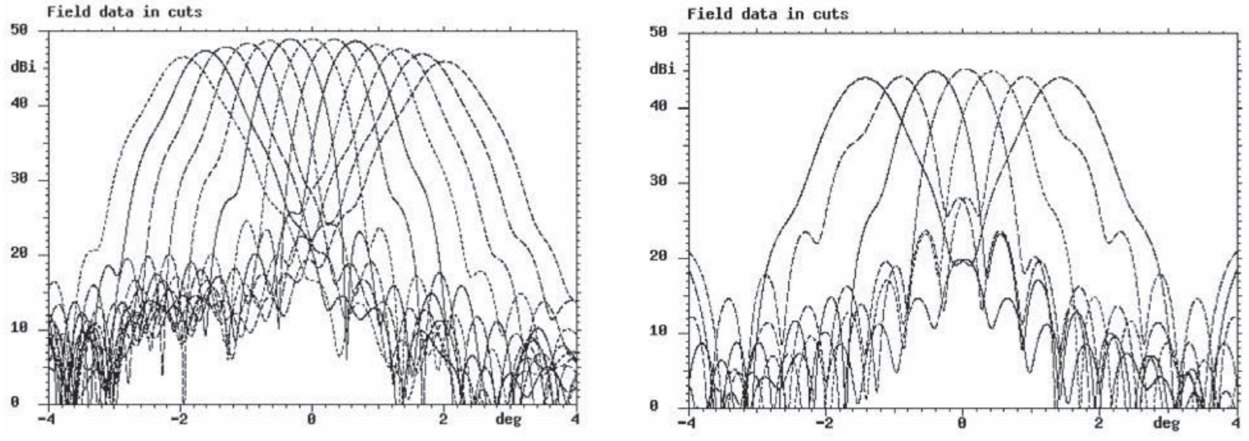
Figure 5: Front fed reflector (Westerbork), single Gaussian feed as a primary source (left) and array of feeds (right). Pattern performances indicate improvements (beamwidth, beam isolation).

Fig.4A, 4B and Fig. 4D show the designs of the multi-beam array feeds build on the basis of the rectangular and hexagonal grid arrays for the prime-focus and offset reflectors, correspondently. The first hybrid system provides the dual-band performance with the required efficiency (see [8] for how to handle dual band performances). The limitation in the number of beams is now recognized as related to the large distortions in the focal field distributions, which start to appear already for the focal distribution related to the second beam (see also Fig.1A). The radiation patterns have desirable characteristics of smooth scanning up to the third overlapped far field off-axis beam (see Fig. 5). Note the narrower pattern for the symmetric reflector illuminated with a feed array, using the concept of rings. For the offset reflector antennas it was possible to support 2 beams more with a comparable efficiency (see Fig. 6) as for the first hybrid system. In fig.6 the status results are shown. The directivity level in fig.6 is relative lower due to a difference in calibration of the absolute feed excitations and also there are only shown a few beams for the different cluster groups (this work is in progress). The envelop of the peaks shows a more gradual behavior for the case of the cluster feed as compared to the single (gauss) feed on the left in fig.6. More results will be shown in the workshop.

Conclusion

Results have been presented as status information of investigations going on. The objective of the investigations is to explore the limitations of multi-beam capabilities of a front-fed reflector (a prime -focus radio-telescope in particular) and an offset reflector antenna. The focal field distributions have been obtained and suggestions have been made to use certain array configurations in such a way, that the aberrations in the focal field distributions, due to the off-axis situation, can be compensated for in part. A result is a more efficient antenna pattern for off-axis directions. Obviously this goes at the cost of complications in the beam forming networking in the focal array. Also polari-

Figure 6: Offest reflector antenna, Gaussian feed as a primary source on the left, array-feed used for the patterns (right). Envelope of peaks more smooth, but excitations still to be optimized, only a few beams are shown (right).



zation properties need to be investigated in more detail, especially when applied in the accurate polarimeter as is Westerbork.

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Stelling

"Proefschriften stellen de lezers teveel op de proef."

D.J. Moelker, proefschrift:
INTERFERENCE IN SATELLITE NAVIGATION AND MOBILE COMMUNICATION
24 november 1998

Multiple satellite detection with a prototype new generation phased array radio telescope

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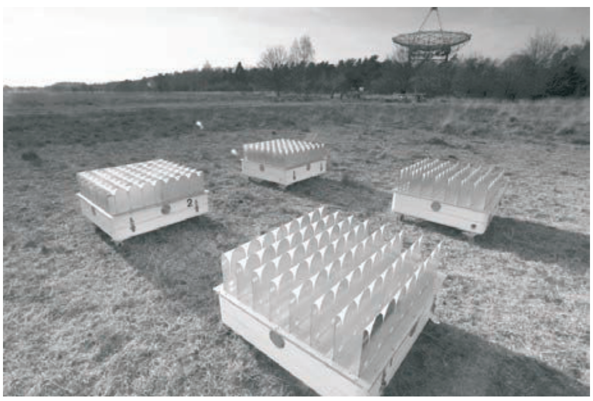
Introduction

A Phased Array Multiple Beaming Radio Telescope Demonstrator

A phased-array radio telescope demonstrator, known as the Thousand Element Array (THEA), is currently under construction at ASTRON. THEA is an out-door phased array system, see figure 1, that is able to detect signals from different strong astronomical sources simultaneously (multi-beaming). It consists of sixteen one square meter tiles (arrays) operating in the frequency band of 600-1700MHz. The beamforming for THEA is done at two levels; Radio Frequency (RF) beamforming on every tile (64 elements) and digital beamforming with the sixteen tiles. Although THEA was designed primarily for radio astronomical purposes, THEA is also well suited for multiple detection and tracking of satellite signals such as GPS. The latter is the focus of this paper, and experimental results such as multiple satellite detection and satellite tracking are presented.

Figure 1: Four THEA phased array tiles, located near the Dwingeloo radio telescope.



International Context

The international radio-astronomy community is currently making detailed plans for the development of a new generation radio telescope: the Square Kilometer Array (SKA). This instrument will be two orders of magnitude more sensitive than telescopes currently in use. ASTRON is in the process of establishing phased array technology, which is particularly attractive for the 200-2000MHz frequency range of SKA. For this, a number of prototype systems have been build, an 8-element Adaptive Array Demonstrator (AAD), and a 64-element One Square Meter Array (OSMA). Phased arrays have the advantage of multi-beaming and interference rejection - both of major interest both in current radio astronomy and in satellite communication. Multiple beams not only allow more users on the system at the same time, but also create possible observations which cannot be done with traditional instruments.

Phased arrays versus refector antennas

Radio Astronomy instrumentation currently rely on the use of large paraboloidal reflector antennas often larger then 25m diameter and at some locations setup in arrays in order to increase the baseline up to a couple of kilometers. Very Long Baseline Interferometry (VLBI), where antennas are combined on the scale of Europe or even space, increases the resolution to sub-milliarcseconds. Limitations arise because these existing telescopes typically have collecting areas below 10.000m2 while observing usually is done with a single beam and limited instantaneous frequency bandwidth. Increasing the collecting area by a large number of

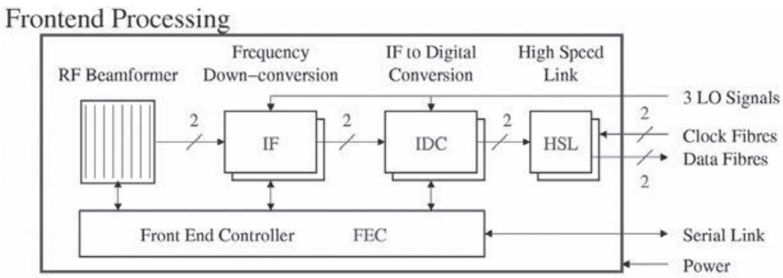


Figure 2: Schematic overview of a phased array THEA tile

dishes would not give the additional benefits that are possible with a phased array system:

- Multi beam capability. Fully independent beams can be realized without the loss of sensitivity, which leads to a multi user system.
- Adaptive nulling. Interference suppression is possible on RF and on digital beamforming level.
- Re-configurability by using sub-array units. Digitized signals of small sub arrays can be used to reconfigure the antenna configuration.

Each THEA tile can form two independent RF-beams from which 32 finer dependent digital beams can be formed when the signals of the 16 tiles are combined in the digital beamformer. Adaptive digital beamforming has been implemented.

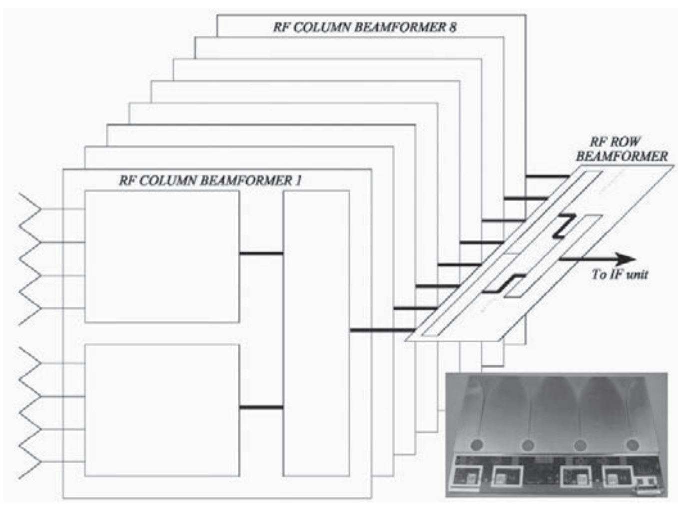
The astron thousand element phased array project (THEA)

Front-end

The antenna element designed for THEA is a taper slot Vivaldy element with a close to two octaves wide bandwidth, Smolders [3]. The antenna is followed by a Low Noise Amplifier (LNA) with a 40 Kelvin Noise Temperature at room temperature. After the LNA the signal is splitted to create the two beams. A Vector Modulator subsequently takes care of the Phase and Amplitude modulation. RF combining networks create the RF signal, which is down converted and digitized with 40MHz 12 bits Analogue to Digital Convertors. The digital output of each beam is transmitted to the THEA back-end with a 1.2Gb/sec fiber link. A schematic diagram is given in figure 2.

The tile, realized for THEA, is a low cost casted epoxy structure. Besides the tile structure, also compact low cost has been pursued with the design of units as the column board, containing the antenna, LNA and Vectormodulators, and the IF receiver unit. For all these parts, multilayer boards have been designed that combine the RF electronics, the digital control electronics and the power supply distribution. The column board e.g. is a 8 layer board with 2 microstrip layers on the outsides (two times signal and ground) and 4 layers inside for power supply and control. For the connection to the row board (figure 3) a single multipurpose connector has been used. With these board designs a significant step has been made in direction of low cost front-ends that are affordable on the SKA scale. The parameters of the dual receiver chain are controlled with a Front-End Controller (FEC). The FEC sets the vectormodulators on the columnboards and the parameters for the receiver unit. It is capable of the storage of 1200 pre-calculated beams, which allows fast beam switching, of interest for the deterministic nulling of moving interferes e.g. satellites. For the power supply of all the units, a DCDC convertor has been used. It creates the required voltages out of a 48 DC supply. An photograph of an opened tile, showing the tile electronics, is shown in figure 4.

Figure 3: RF beamformer architecture for each tile, showing the column and row beamforming stages. The inset shows a picture of a column board, with 4 antennas, amplifying and beamforming network.



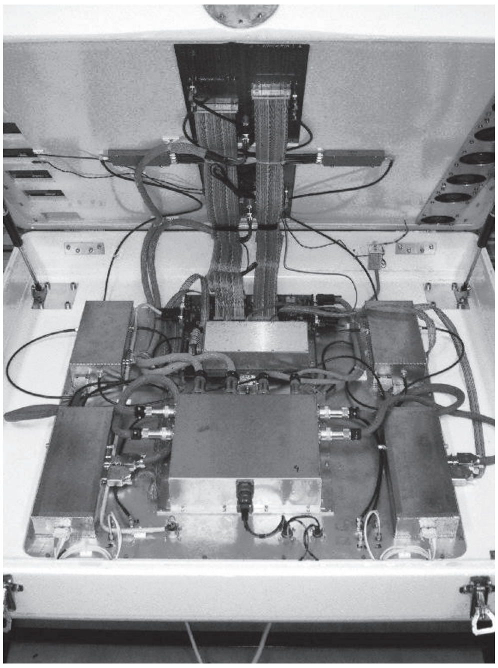


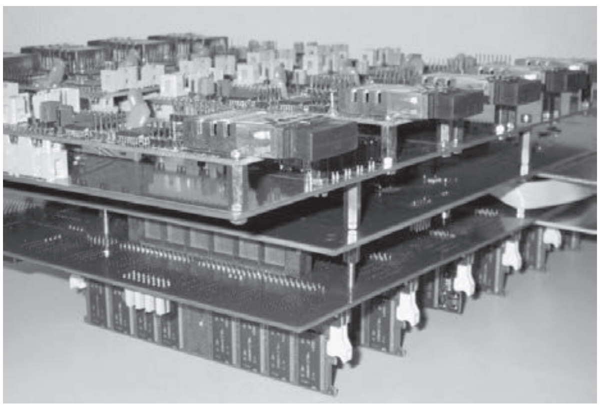
Figure 4: An opened THEA tile. The column boards are placed on top of the tile-lid, inside the tile is visible the tile electronics described above.

Back-end

In the digital data processing of the THEA, two major parts can be distinguished: the Adaptive Digital Beamformer (ADBF) and the Reduction and Acquisition unit (RAP). The ADBF consists of the Adaptive Weight Estimator (AWE) and the actual digital beamformer. The RAP consist of a memory / beam selection board and a digital signal processing board.

The backend receives its signals via an 1.25Gbit/s serial fibre data stream which is converted to parallel in the High Speed Link (HSL) receiver. In order to handle the resulting parallel lines, up to 400, a high density connector is used in combination with a dense 'sandwich' structure: the HSL

Figure 5: Photograph of the assembled high speed link, the digital beamformer and the RAP unit.



fiber receiver board is plugged directly on the DBF while the DBF is placed on top of the RAP unit, figure 5 gives a picture of the three boards. The complete assembly is mounted in an industrial PC in a standard PCI slot. The final output of the system is then stored on a hard-disk or on storage CD's.

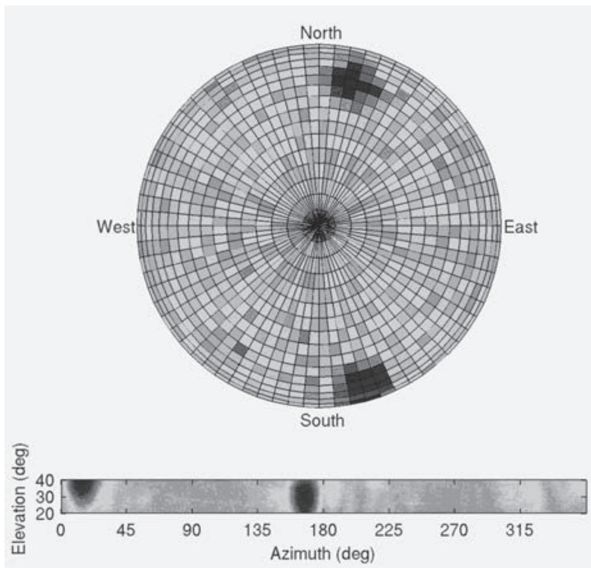
The Digital Beamformer is controlled by the AWE. The AWE determines from snapshots of the raw data the optimal, in terms of RFI suppression, complex weights of the DBF. For RFI studies and multi-beam experiments, memory has been placed on the selection board. With this memory 16 channels (beams) can be stored for 0.8 seconds or one channel for 12 seconds.

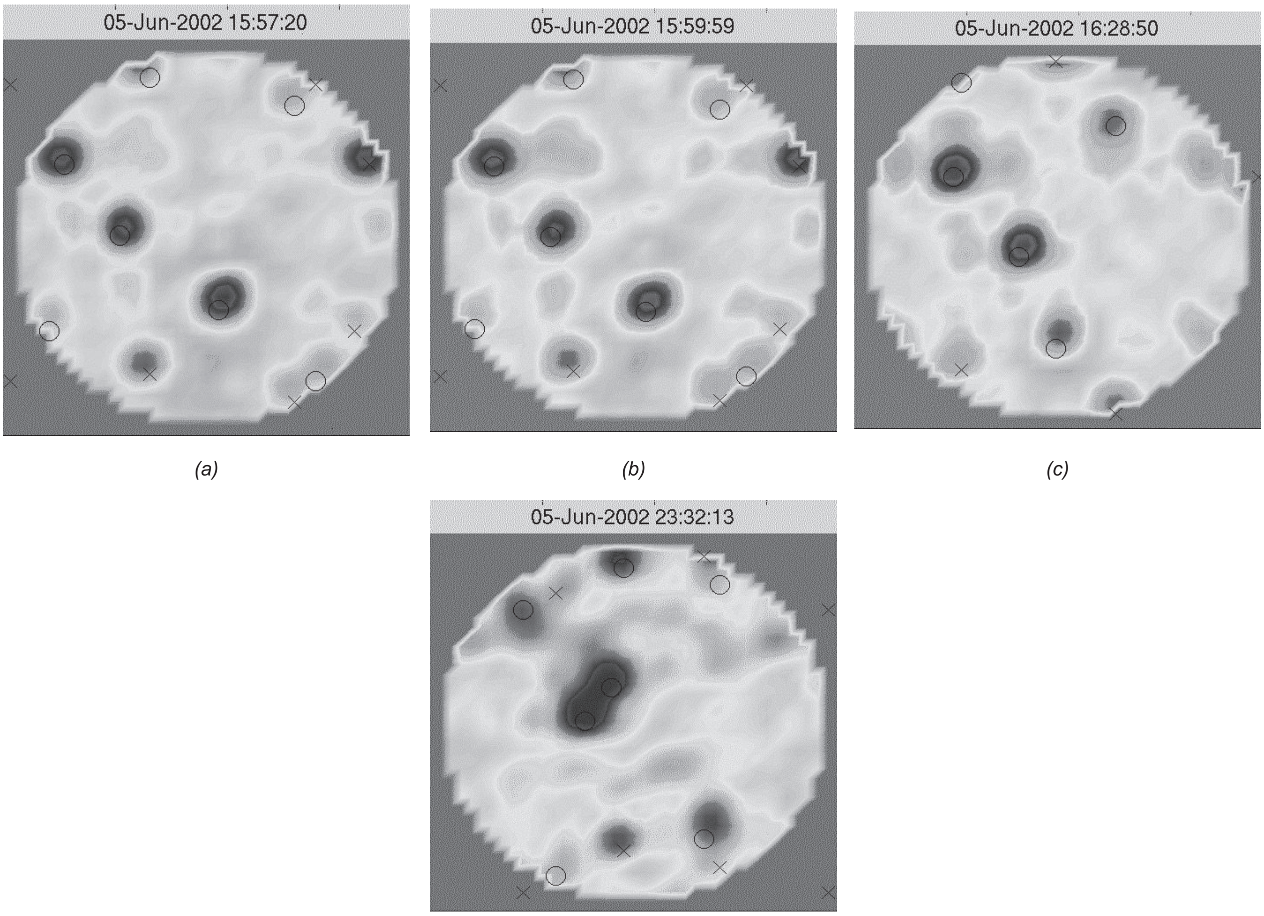
The processing unit performs a 1024 points FFT. The number of integrations can be set with a minimum of 32 spectra (100µs) and a maximum of 4000 spectra (100ms). With post processing the integration time can be enlarged up to 1 hour. The processing unit is capable of performing autocorrelations of two channels simultaneously or complex cross correlations of two independent channels, with a bandwidth of 20MHz.

Satellite detection and tracking: experimental results

The first experiments with THEA were done at the tile level, without using the THEA backend but using a fast spectrum analyser instead. One of the two tile RF beamformers was used in a fast scanning mode to scan the entire sky. Figure 6 shows a

Figure 6: Afristar satellite observation with a THEA phased array tile.





(a) (b) (c)

(d)

THEA tile observation of the recently launched digital audio broadcasting satellite Afristar. It was easily detected and it was used for several system tests. Afristar transmits a carrier with modulation at 1480 MHz; the satellite is geostationary and could in principle be used for the calibration of the system. At the outdoor test facility at ASTRON, the Afristar satellite showed up at 26° elevation and 165° azimuth. Some basic array aspects are demonstrated with this measurement. Due to the spacing of the array, $\lambda/2$ for 1200 MHz, on a rectangular North-South grid, we expect (and observed) Afristar also to appear in a grating lobe when the array is pointed at 15o azimuth. The beamwidth for the 1 meter tile can be calculated width $\theta_{HP} = \theta_{0/\cos(\theta)}$, where θ_{HP} is the half power beamwidth and θ_0 is equal to 17° at 1480 MHz for this aperture. For this observation, the observed power difference between the beam maximum and the sidelobe minimum is about 15 dB.

Figure 7. GPS observations with a THEA tile phased array, showing the RF beam output power scans over the entire sky (down to 20 degree elevation at four different times. The dark spots are the observed GPS satellites.

In addition to the Afristar measurements we also were able to detect and track multiple GPS satellites using a single THEA tile. Figure 7 shows four snapshots out of a 24 hour measurement programme. The figures shows the array output power (white: low power, black: high power) of RF beam scans. These scans needed 3.5 minutes to complete, and each scan covers the entire visible sky downto an elevation of 20 degrees. Visible as dark spots are the GPS satellites. The expected satellite positions are marked with circles; the expected grating lobe positions are marked with crosses. There is fair match between expected and observed positions. Figure (a) and (b) show to consecutive scans. The satellite motion is clearly visible by comparing figures (a) and (c). In figure (d), taken several hours later, the satellite constellation is (as expected) quite different.

Conclusion

The first single THEA tile GPS and Afristar observations were successfully carried out with the THEA proto-type phased array system, which is intended to demonstrate the potential of this concept for application in the Square Kilometer Array, but also for application in satellite communications systems. The next steps to pursue are application of deterministic and adaptive nulling, both using the a single tile and using all available THEA tiles. An interesting option is the observation of satellites with one beam while using the second beam for RFI suppression purposes.

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Stelling

"Iemand die een goed theoretisch inzicht heeft kan vaak de praktijk makkelijk leren. Omgekeerd is dit niet altijd waar."

S. Stramigioli, proefschrift:
FROM DIFFERENTIABLE MANIFOLDS TO INTERACTIVE ROBOT CONTROL
4 december 1998

Pricing in the 'Newest Economy'

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Recent years have shown a dramatic decline in telecommunications profits. At least three main reasons for this can be identified:

1. ***the lack of proper business planning in the IP services sector resulting in high investments which were not met by sufficient revenues;***
2. ***over-extension in banking loans to cover for wild investments in UMTS licences, resulting in interest commitments that put a too heavy burden on normal revenue generation; and***
3. ***the incredible price erosion for trunk capacities, resulting in a serious almost non-recoverable gap between investments per megabit and revenues per megabit.***

Only recently we have seen major and seemingly successful companies (Global Crossing, Carrier l, GTS, KPN-Qwest[1]) hit the rocky shores. It is clear that the telecommunications world operates in a non-sustainable business model which cannot last much longer. This paper analyses the problem causes and gives directions for solutions for a return to a potential healthy telecommunications business environment.

Current Situation

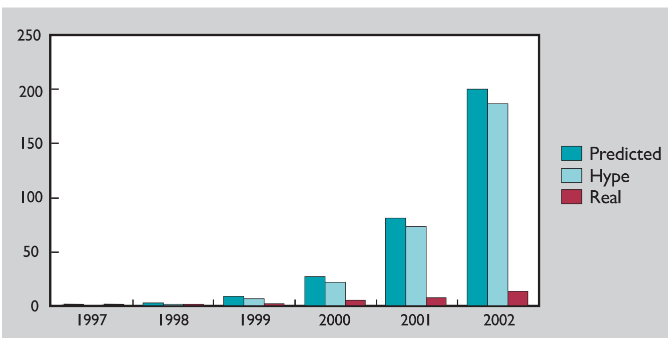
The past 30 months have shown that a complete industry sector could turn from a very prosperous situation into a very worrisome state where one company after the other hits the rocky shores and needs to be salvaged or completely disappears. The first point to make here is that short-term prosperity is not the same as long-term health. The comparison with a couple of phrases comes to mind: building castles on ice—when the ice melts, the castle disappears; building air castles—the bubble can burst. Maybe the combination of the two applies to the current situation. In general it can be said that three main causes can be identified for this miserable situation.

Cause 1. It started with the explosion of the Internet TCP/IP services. Triggered by the first steep exponential growth of residential use companies started to make growth projections and to commit to investments in cable systems that should meet the projected demands. Fierce competition, price erosion, huge over-capacity and failing demand caused the downturn.

Cause 2. The second main factor which initially affected mainly the incumbents is again far over-optimistic planning of mobile telecommunications services, culminating in the infamous UMTS auctions. This initially brought a couple of companies almost on their knees, but a direct effect was that the banking sector became over-extended in the telecommunications portfolio and had no room for further investments in telecommunications and related developments.
Governments can be held partly responsible for forcing these mechanisms.

Cause 3. The third factor lies in the fact that deregulation drove new market entrants into huge infrastructure investments which by a combination of

Figure 1: Bandwidth hype



1 At the time of writing this paper, warnings of near bankruptcy of KPN-Qwest appeared in the press.

price erosion and failing market shares never came to fruition.

Despite the fact that the industry is in a bad situation it can be stated that telecommunications is still a growing market segment and if the hype effects are taken out of the trends, a still healthy normal growth pattern remains (Figure 1). Existing users increase their voice and data volumes constantly, globalisation continues and requires new service types, new connection strategies and new applications. Therefore there is basically no reason why the telecommunications industry could not be a very healthy segment.

How Did it Come That Far?

The Internet hype

Since the first boom of the public Internet and the WWW, American and subsequently European visionaries and marketeers forecasted that IP would be the one and only solution for all applications to be used by everyone. Ordinary telephony would be replaced by IP-voice services; companies would gradually move from physical to electronic business models. Incumbents and new telcos anticipating this development started building the terrestrial and cross-ocean fibre infrastructures to support the exploding traffic volumes. At the same time in this euphoric state everyone with a potential idea was able to raise money, start a company to develop the idea and sell it on the potential value before any results were available. In the ownership chain people made huge financial profits on shares but the last owner often faced the problem of a not-operable or nonsellable service.
Many corporations had just uplifted their telecommunications infrastructure by investing in frame relay data services. The forecasted rapid take-off of IP virtual private network (VPN) services did not take place and still has hardly appeared on the map because customers have no money for new investments and rightfully they do not yet trust the quality, the reliability and the security of the Internet-based services.

Figure 3: Investment versus yields

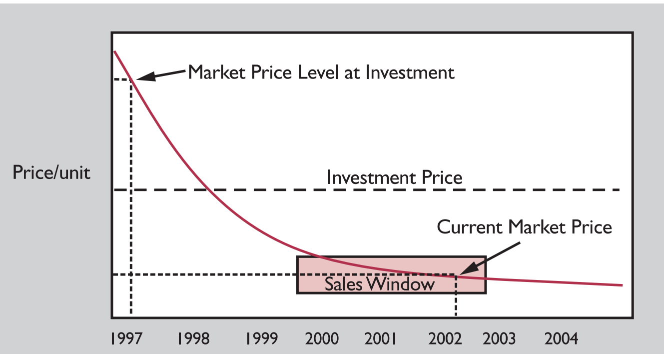
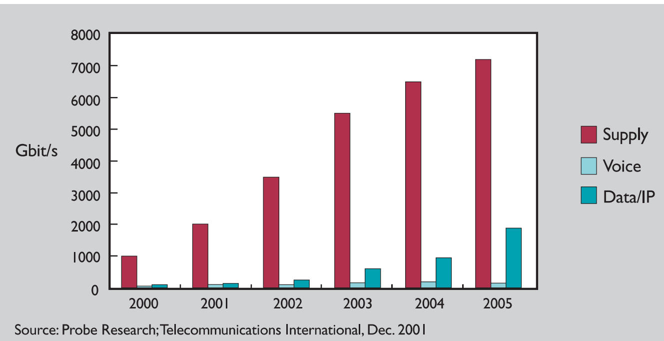


Figure 2: Installed bandwidth versus demand, intra-Europe



Source: Probe Research; Telecommunications International, Dec. 2001

The infrastructure

Predictions for required capacities to carry all the IP traffic ranged from doubling per year to doubling per quarter. MCI-WorldCom for instance preached at each and every seminar which they attended that the industry should build for a doubling per quarter and they warned for disastrous effects if it was not done (Figure 2).
At the same time the new telcos were building European-wide country and city rings, all in parallel, all suffering from the same problem of the last mile to the customer sites and from fierce competition which was stimulated by national and European regulators.
As a result of new technologies, the competition and poor growth, the newly built infrastructures are now estimated to be 90% idle (non-lighted) and the unit prices have fallen about 90% in the same time [1].
Companies can today recover only 10–25% of their investments on a unit basis. This means that basically each deal yields not enough to recover costs and is most of the time loss-making (Figure 3).
An article in *Communications International* by Elizabeth Briddlecombe provides interesting details.

The mobile world

We have seen a number of now almost classic mistakes in the telecommunications world. The mistakes are that clever developers design things that are technically feasible, beautiful and attractive. They expect that the world sees it the same way. Good examples are ISDN, Videotex, ATM, WAP—beautiful designs but commercial disasters.

The Internet/WWW is about the only service which reached its position by shear customer demand and requirements. The developers in this case were running after the facts while trying to catch-up.
With the boom of GMS usage it was no surprise that the combination with IPInternet was made. Forecasters dreamed of personalised location-based IP-based services for the mobile customer; for students without money; for stupid traveling businessmen who do not know where to go, where to sleep or where to eat; games were going to be used by youngsters (games/ SMS), infotainment and pornography by adults, and all types of business oriented applications for people on the move. In reality games and pornography are doing well[2]. These people assumed that customers on the move really want to browse the Internet, receive advertisements, shop offerings on their mobile phone handsets while walking or driving through the crowds. These untested scenarios would scream for broadband mobile services, and GPRS followed by UMTS appeared on the radar screen as the next developments, all based on the assumptions that users would USE it and PAY for it. During two years of seminars nobody has come forward with even one killer application (unless interpreted in a very literal way), neither has the industry indicated possible price levels for usage.

A next example of the classic mistake by technology push was born.
Since governments control the airspace and the frequency spectrum they found a very attractive source of fresh money by selling licences via auctions and beauty contests to potential operators. These made it possible for governments to cash in 10 years of tax advances, leaving the licence buyers near broke or at least over-exposed with the banks. GSM in the meantime is reaching market saturation. The real bad news is that the payments for licences have only covered the right to deploy UMTS. To be able to operate the service, comparable amounts of money have to be invested in new infrastructure, development of applications and marketing. Hardly any company has started to make these investments for deploying the UMTS. KPN has introduced IMode with GPRS and probably awaits its success before investing in UMTS. It must be stated here that market trials where people can try the service for free are never representative for the later success under normal commercial conditions where users have to pay the price. These tests are only good to test the proper operations of services.

The money trail

Of the funds invested in new fibre networks 70-90% is dead money because of idle capacities.
Money paid for UMTS licences is dead money at least for the next five years and comparable amounts of money have to be invested first in infrastructure, and service applications and marketing before these investments can be brought to life.
Venture capitalists, investment bankers and other funding suppliers have learned that ‘castles built on ice’ do not bring the expected profits and they have been decreasing and cutting off the money flows. Companies are falling over by the day because they are in a non-sustainable business environment where, although revenues are growing, the losses grow as well and sometimes faster.
Banks have a policy to divide their money over various industry segments. Currently the telecommunications sector is over-exposed. This means that for new telecommunications developments even with very positive expectations no money can be found because banks must invest in other industry segments to restore the balance.

The New Economy concept of the late-1990s

Taking this concept slightly cynically, it can be summarised as ‘do without thinking’. Entrepreneurship in this new style has failed royally. Because of this failure companies had to sell their products and services at just any price to make a bit of contribution and therefore giving discounts was the competitive and suicidal tool. The customer gets what he wants at any price (sometimes no price) because having the customer was more important than (profitable) revenues. ‘The many *dot.com* have turned into *dot.gone*’.
The concept of free service became popular. Customers liked it but rapidly required service quality comparable to regular services. This requires additional investments and operational efforts.
‘When something is free, usually someone else is paying the bill.’

2 If pornography was removed from the †Internet, the bandwisth capacity would reduce to about 50% (*Communications International*).

The New Economy has proven not to be a viable concept and the exploding business balloons all around demonstrate that sufficiently.
Something else is needed.

The Newest Economy of 2002

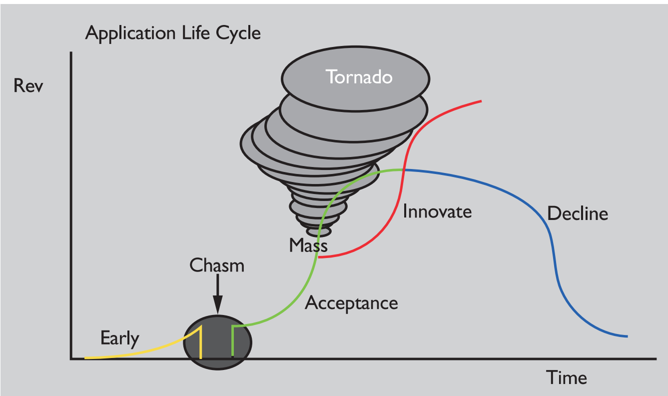
In a recent column for the FITCE Forum the concept of the *Newest Economy* was introduced. The Newest Economy is based on a very simple concept namely *PROFIT*. The telecommunications industry has obviously forgotten that a long-term successful enterprise needs profits to make the success sustainable. To refresh some fundamentals: *profits will be the result when the revenues are higher than the costs*. To implement this and to run a business so that indeed profits are generated is a bit more complex than just the simple equation given above.
Important elements or conditions are:

- each individual service must be cash flow (net present value(NPV)) positive after a defined time frame;
- each customer must be profitable on the total portfolio sold to him almost from the beginning;
- all financial analysis must be based on integral costing and pricing. (Exceptions to this rule can be temporarily allowed for new product introductions but they should be managed very carefully.); and
- the Free Service concept is no longer viable. Customers must pay a fair price for services they use.

Solution Directions

Implementation of the Newest Economy requires a series of carefully planned activities including:

Figure 4: Geoffrey Moore's chasm and tornado Application Life Cycle



Policies in general: companies must state what they want to do in their business, how they want to do it and to define some key values to be achieved (like a x% profit margin after tax).
Pricing and costing: product pricing should be done in such a way that prices incorporate direct + indirect costs + allocated overhead costs. If the staff drives Porsches as company cars the products must pay for those as well.

Business planning geared for profits: business planning must incorporate all eventualities and especially should take into account the whole system of discounting. Discounts are to be considered as a risk and cost factor and must be built into the pricing.

Control of the sales process: the common practice in the industry is that sales persons are remunerated on a percentage basis of the revenue value of the sale when a sales has been closed. It is recommended that sales commission should at least be partially based on:

- the annual value, stimulating multi-year contracts and account management;
- the profitability of the deal and not just the revenue value; and
- the time a service becomes operational and starts generating revenues. There could be a substantial time lapse between contract closure and first revenue in the bank.

Sales is by nature more driven by closing a deal at all cost than by the profitability of the deal. Discounts are a very dangerous tool and they should be controlled forcefully.

Service development strategies: The time-to-market requirements for new products are becoming shorting and shorter. This means that little time is available for market testing. This raises the risk level of failed introductions. It is therefore necessary to control the service development steps rigorously and make optimal use of available resources and opportunities. Stopping a project in time can be a lot cheaper than launching a service too late. Many developments will not end in success. The 'chasm and tornado' [2, 3] theory is very important (Figure 4) because it warns against over-optimism in launching new products and services. Often development projects are undertaken without a proper justification but under the heading of strategy [3].

Discount budget control: As stated above it is very important to control the discounting. Bringing the discount into the prices is one thing; allocating budgets to the various responsibility levels in a company is another very helpful tool. It basically means that if for some 'strategic' reason the sales boss decides to give an extra non-standard discount for a bid it will be subtracted from his budget and not from the productmanagement budget. It is a fair way to manage performance and give performance bonuses. It is also an additional tool to watch over profitability.

For each of the above given elements there are complete textbooks and study programmes in the top business schools. They should not be taken lightly.

Bandwidth price erosion

The given situation of the dramatically fallen unit prices of bandwidth capacity is an issue in itself. The new companies that have invested heavily in new fibre capacity have a couple of options, depending on the strength of the finances.
If they are strong enough like some of the incumbents they can take their losses and start selling the network at prices that are profitable against the new cost base. This will mean in general that prices for bandwidth will go up. Interestingly this has already been announced by KPN-Qwest and also by KPN itself. They are raising the price levels for international capacity, and in the case of KPN for the ADSL connections (25%).
Companies with a weaker purse have basically two options:

1 be bought under a M&A (mergers and acquisitions)[4] programme and after reorganisation continue with the business;
2 continue with the business as a lossmaking enterprise and go broke eventually. Other going companies may pick up the pieces at reasonable prices and recreate a profitable business. This is a Darwin-type approach of survival of the fittest. Although we may not like the sound of this, it will sort out the telecommunications environment relatively fast, repair at least some of the share values and restore the positive image of the telecommunications sector.

The victims of such a process could apply for some help from the governments—probably with little success—as their regulating bodies are at least partly responsible for this situation. Competition was almost forced upon the market and the auctions for UMTS made it worse.
A new approach has now been proposed (for instance by a company named Q-Optics) where bandwidth from various owners is brought into a pool structure and is managed as such. Companies in need of capacity, especially for the short term, can arrange a lease contract for the required capacity and period with the pool manager. The unit price is of course higher but the cost of ownership is much lower.

Attention Points

- Data volumes have surpassed the traffic volumes for traditional voice—a statement made proudly by companies and analysts who seek arguments for infrastructure investments, including UMTS. The raw fact however is that almost nobody in the world has made any profits on data (IP) traffic. The only profitable service is traditional voice with perhaps a bit of profit on the traditional frame relay. One should not too easily migrate to voice-over-data solutions. Only if substantial cost savings and acceptable quality can be achieved it may be worthwhile, for instance, on incompany networks.
- The upfront investments necessary in infrastructure to start and run a telecommunications business are more than substantial. Severe audits on the business case and on the incoming business results may avoid serious shipwrecks later.
- The concept of 'The customer is king and he should always get what he wants' is still valid; however, under the important new condition that the king should render profitable revenues. Nobody needs a lossgenerating customer (king). Customer satisfaction must go hand in hand with supplier satisfaction.

3 3 'If you want to do something, but lack the business justification and still want to do it, you call it strategy.' (Gerrese 1997)
4 Sometimes called: murders and assassinations.

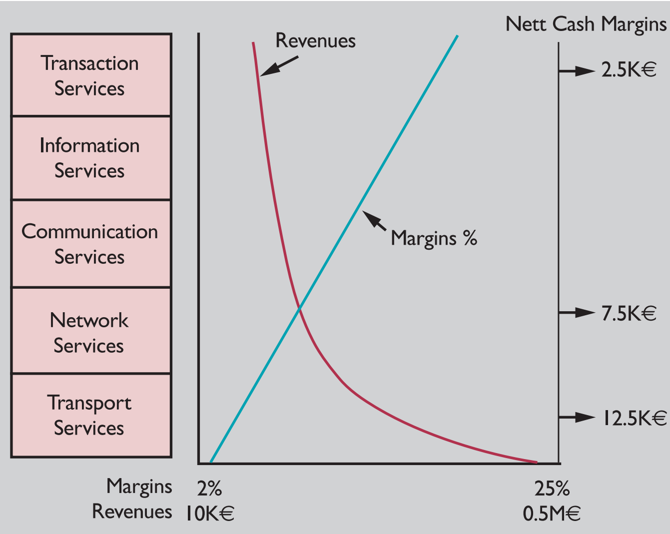


Figure 5: Revenue–margin relation

- The role of European and national regulators should be reconsidered. The artificially created competition climate has stimulated a series of new companies to enter the business. In general, realistic possible market shares were insufficient to create momentum and a sufficient revenue base to ever become profitable. When 10 companies each claim to reach a 20% market share something is bound to go wrong.
- Many operators try to escape the revenue trap by attempts to climb the value chain. The main reason is that higher value products and services generate higher profits per unit than for instance bandwidth and transport services (Figure 5). It is often overlooked that a small percentage on a large amount of money (bandwidth) may be a lot more cash than a higher percentage on a unit of valueadded service. Apart from the cash aspect, it requires a totally different skill set in management and sales to run a valueadded service (Figure 6).
- Non-standard bids should be managed very carefully, especially with respect to pricing. If a non-standard development is customer-specific, that customer should pay in full. If the development can be shared (become a standard feature), one can spread the costs and price accordingly.

Conclusions

1 Although the industry as a whole is still in a bad shape it must be possible to recover since telecommunications as such will not disappear and will continue to grow.
2 Companies not aiming for profit will disappear and the ones which organise their commercial and administrative systems such that they are profitable will be able to survive successfully.
3 Companies that are overstretched in the bandwidth area will either be bought or go broke. The survivors will pick up the remains at cheap cost and will build new profitable businesses creating new shareholder value.
4 The concept of profit making is called the *Newest Economy* as a follow-up on the failed New Economy concept.
5 Regulators should leave the business alone or should have the weakest influence possible.

Transaction Services	Direct + Indirect + VA Resellers + Integrators, Skills; Professional Services + Application Providers
Information Services	Direct + Indirect + VA Resellers + Integrators; Skills; Professional Services
Communication Services	Direct + Indirect + Distributors; Skills
Network Services	Direct + Indirect Sales, Increased Headcount
Transport Services	Direct Sales, Limited Headcount

Figure 6: Sales channel options/skills

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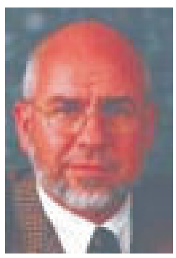
[1] The Silence of the Lambdas. Report by Yankee Group.
[2] MOORE, GEOFFREY A. Inside the Tornado.
[3] Proceedings FITCE Congress 2001, p. 159.

Biography



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Jos Gerrese graduated in 1973 from the Technical University of Delft—Telecommunications Technologies. Currently he is president-owner of GANESHA consult, which he started in August 2001, operating in the telecommunications/ICT and interim management arena. He began his career with PTT Telecommunications—now KPN—and held a wide range of positions in research, marketing, organisation development and new services introduction. From 1984–1989 he was director of a post and telecommunications consultancy firm Nepostel in Indonesia responsible for South East Asia. From 1989 onwards he held senior productand marketing-management positions in KPN, AT&T-Unisource and latest Ipulsys until May 2001. From 1990–1993, he was president of a European telecommunications operators consortium EBIT, later GLOBAND, building the first switched broadband network over Europe. He is a frequent speaker and has given lectures at over 40 international telecommunications seminars throughout Europe on a wide range of topics over the last two years. He is a respected member of FITCE in which he held several positions.

Stelling

"Het 'abstract' van een artikel is vaak te abstract."

H.J.L.M. Vullings, proefschrift:
BIOMEDICAL WAVEFORM VALIDATION
4 mei 1999

Service Transparent Full Fibre Access Network

Harry J Goes, J. E. W. (Bert) Winkelman
and Aron van Zijl

This paper presents a solution for a full fibre access network, which is service transparent and supports the business model of an access provider who is independent of any service provider. The transport technology is Ethernet over fibre. The interface at the customer premises is 10/100BaseT Ethernet. Aggregation of traffic is performed at layer 2. A service intelligent IP layer is provided at the interface between the access network and the service provider's network. Subscriber operations can be fully automated.

Introduction

The residential broadband access market will be stimulated by two factors:

- innovative broadband services like on demand video and audio distribution, and
- the penetration of web-based access to for example banking, shopping and government services.

The acceptance of new services by residential users is heavily influenced by the convenience of use. Adequate network response times, enabled by sufficient bandwidth in the access network and the aggregation network are required.

A multitude of technologies supports broadband access today: digital subscriber line (DSL) (using copper lines), cable, wireless and optical (using fibre). While DSL technology and cable are ready today for volume deployment, for Greenfield deployments technologies using fibre are still limited to high revenue applications. The reason for this is the high cost of the optical technology (optical/electrical components, connectors, optical distribution frame space requirements). Wireless technologies suitable for point-to-multipoint bidirectional traffic have similar cost problems. In addition, these solutions are much more bandwidth limited than optical solutions.

From a business perspective, copperbased technologies (DSL) have the drawback that deployment is done over copper infrastructure. This infrastructure is owned by the incumbent, who in this way has a considerable advantage over other service providers (SP) offering this service, even though access to the incumbent's copper infrastructure is regulated today. Wireless, cable and fibre are the technologies where, in the access area, incumbents do not have this competitive advantage.

In order to stimulate the creation of broadband access infrastructure, a number of local communities have taken the initiative to build a fibre access network [1]. This network should be transparent for all known broadcast and communication services. Service providers should be able to offer independently any combination of services to the end-users. Bundling of services or a monopoly for a specific service should not be forced by the solution. It should be possible to operate the access network as a stand-alone business.

Requirements

End-user services and the operational model of network operations determine the requirements to the solution. In this section an inventory is made of both classes of requirements.

End-user services

In Table 1 an overview of the end-user services is given. We take into account a 'triple play' scenario, because we believe that, if we limit the services to pure Internet and voice only, the network will not generate enough revenue. Table 1 lists the services that the network should support.

Service transparency is the key requirement for a viable solution.

Of all the types of customers, large enterprises have high traffic volumes and specific services. Requirements for this type of customers are excluded. This

Service	Type of Customer	Required Bandwidth	Additional Information	CPE Supporting the Service
Internet access, data VPN	Residential	40 kbit/s average	Asymmetrical, downstream max. 2 Mbit/s	End-user PC or CPE router
	SME	128 kbit/s–2 Mbit/s	Symmetrical	End-user PC or CPE router
	Enterprise	2 Mbit/s–155 Mbit/s	Symmetrical	
Voice offered as VoIP, voice VPN	Residential	0.1 E × 100 kbit/s	Symmetrical, low latency and jitter	Voice gateway, IP phone or softclient
	SME (PBX trunk)	0.5 E × 100 kbit/s	Symmetrical, low latency and jitter	Voice gateway or IP phone
Video distribution (HQ TV)	Residential	4 ×5 Mbit/s	Asymmetrical, assume 4 sessions in parallel, limited delay variation	Set-top box
Audio distribution	Residential	4 × 12 kbit/s	Asymmetrical, assume 4 sessions in parallel, limited delay variation	Set-top box

Table 1: End-user services

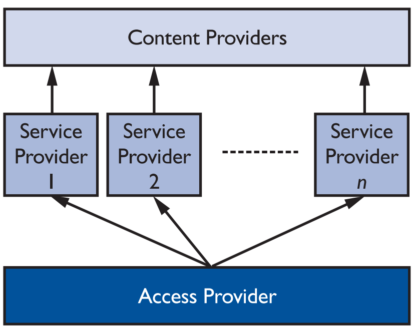
is acceptable, because these enterprises will be mostly located in business parks, which have a purpose-built fibre infrastructure.
From the information provided in Table 1 we can draw the following conclusions:

- Bandwidth requirements for the last mile are maximum 2 Mbit/s upstream, maximum 20 Mbit/s downstream; a 100 Mbit/s physical interface provides a future-proof solution for residential and SME type customers.
- Quality of service (QoS) requirements range from none for the best effort residential Internet access to specific requirements for interactive services, such as voice, and distribution services, such as video and audio on demand. QoS requirements are quantified by average throughput, peak throughput and delay variation.

Other requirements are:

- security, no interception of communication by unauthorised parties;
- authentication, authorisation and accounting (AAA); and
- protection of the network against spoofing and denial of service attacks by any party connected to the access network.

Figure 1: Business model FTTH access provider



Network management and customer-relations management

The business model that the access provider adopts heavily influences the requirements (see Figure 1). In the model given in Figure 1 businesses may be integrated vertically; that is, the access provider could also be a service provider. The access provider in this model limits its business to wholesaling 'bit pipes' to the premises; the access provider delivers a connectivity service to the service providers. These bit pipes are leased to service providers, who may offer a single service or a service package. We have based the network management and customer relations' management requirements on the assumption of access provider and service provider being independent businesses. The interface between these businesses must be clearly defined and of manageable complexity. The requirements are discussed below for each area.

Subscriber operations

The access provider must be able to add, modify and remove subscribers on the network.
Provisioning of a specific service should be fully automated. Initially, the access provider will provide connectivity for every service offered by the service providers, who have access to its network. However, adding a specific subscriber to a service

or removing a subscriber from a service should not require any manual intervention by the access provider. This applies especially to parameters related to the subscriber's CPE (set-top box, telephone set). The subscriber ('self-service') or the service provider could initiate the provisioning.
Regarding *accounting* a solution should support the following options:

- flat rate to each individual subscriber for the access network combined with fixed fee plus usage-based fee for service providers (in the extreme case the flat fee for the individual subscriber could be zero); and
- flat rate plus usage-based fee for individual subscribers combined with flat fee ('interconnect fee') for service providers.

A usage-based fee would be based on volume of transferred data. A flat rate could be differentiated by the maximum bandwidth upstream and downstream supported on the last mile. However, this would require service level knowledge by the access provider.
Regarding *maintenance* the solution should support detection of transmission failures in the last mile. On-demand go/nogo tests should be provided, as well as means to monitor the transmission quality of the last mile for a limited number of subscribers on the network simultaneously.

Service provider operations

Provisioning: The access provider must be able to add, modify and remove a service provider service. The description of the service shall include the QoS requirements and common data for authentication and authorisation of the subscriber to the service. A two-level authentication is required; the first level is performed by the access provider and the second level by the service provider.

Maintenance: A service provider should have the possibility to verify if a subscriber is accessible.

Accounting: The access provider should not have to supply any data to the service provider for billing of services to the individual subscriber.

Network Operations

Network operations should be fully automated to achieve the lowest possible operational cost. Equipment redundancy and path protection should be provided from the first aggregation level up to the interface to the service provider's network. Restoration times should be such that service is not disrupted.
The network equipment should support auto-discovery of the network elements and network configuration, to minimise the provisioning effort.
Fault management functions should include tools to provide automatic localisation of the fault to the level of a field replaceable unit or transmission facility. Functionality required for the last mile is stated under 'subscriber operations' above.
Performance monitoring tools should provide insight in the actual traffic on the network, identify trends in network usage and potential bottlenecks.

Cost

The capital expenditure (CAPEX) and the operational expenditure (OPEX) should be as low as possible.
Regarding CAPEX, the solution should be competitive with other broadband network solutions like DSL and cable. CAPEX cost for DSL access solutions are in the range of €170–230 for the active components. For an HFC network the investment per home passed is approximately €250 (network upgrade) to €400 (rebuild), excluding CPE [2].
The Cahners group [3] expects fibre-to-thehome (FTTH) deployments to become a viable alternative to other broadband technologies when the cost for the last mile is in the order of €500 per subscriber.
Based on our own research we conclude that a cost target for the active components of €350 per subscriber line is acceptable initially. The long-term goal should be to reach parity with DSL and HFC.

Solution Architecture

Ethernet technology has been used in LAN environments for many years and is now advancing into wide area networks.
Ethernet is popular because of its simplicity, its low cost and its large installed base. The limitations of Ethernet with regards to absolute quality of service, security and broadcast/multicast traffic are compensated for by new protocols like Internet group management protocol (IGMP), multiprotocol label switching (MPLS), IPv6, etc. Therefore, Ethernet has become the technology of choice for FTTH deployments today. The proposed network design has the following layers:

- ***Access layer*** At the access layer subscribers are connected to a VLAN switch (access switch); the access layer has a physical star topology. The location of the VLAN switches depends on the

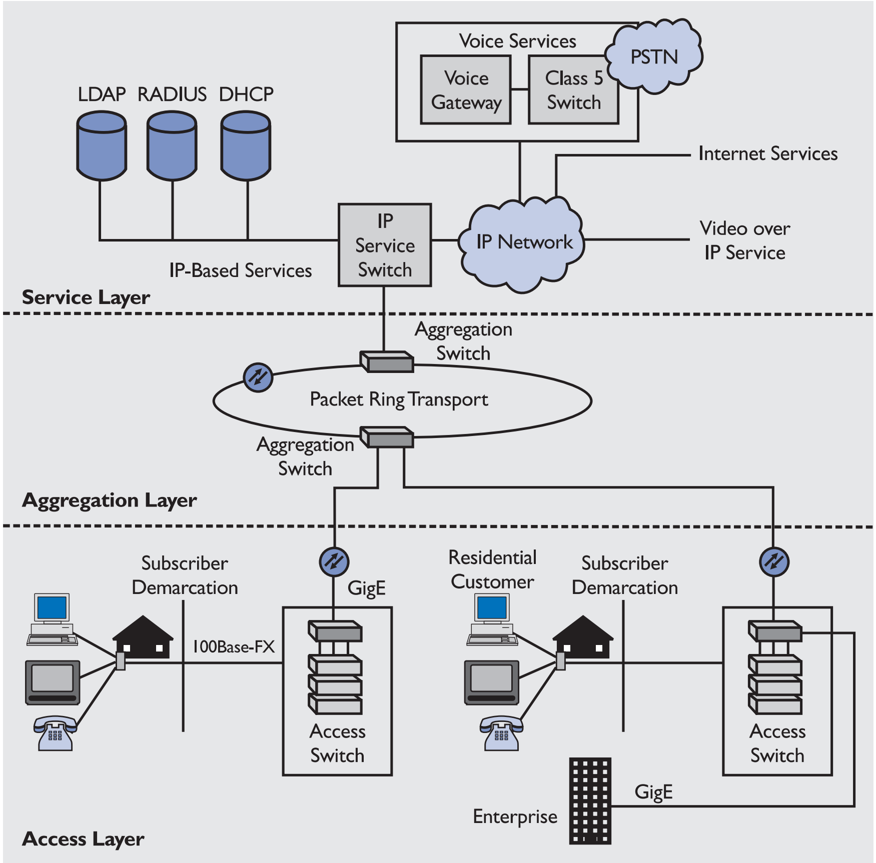


Figure 2: High-level network design

reach of the Ethernet connection. Multiple access switches can be stacked and connected to the aggregation switch to provide scalability and reduce the number of required uplinks.

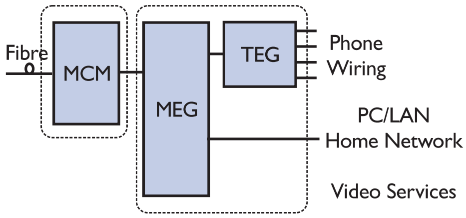
- ***Aggregation layer*** At the aggregation layer multiple Gigabit Ethernet links coming from the access switches are aggregated into the transport network by Ethernet switches (aggregation switches). Ethernet connections rely on spanning tree protocols (STPs) for resiliency at the Ethernet layer. However, this method offers relatively slow convergence of the network in case of a link failure. Many vendors have implemented enhanced proprietary forms of STP that offer faster network convergence. Spanning tree protocols do not offer protection of the Ethernet links at the transport layer. A ring topology of this layer, based on Ethernet over SDH overcomes this deficiency. The resilient packet ring technology as proposed in the IEEE 802.17 Working Group can offer link restoration similar to traditional SDH protection schemes.
- ***IP service layer*** The IP service layer provides IP QoS, addresses scalability issues and supports the necessary functionality at the interface to service provider networks.

The high-level network design is shown in Figure 2.

Architectural choices

The following of architectural choices have been made:

- Subscribers are connected in a physical star topology in the access layer. No passive or active equipment between the subscriber and the access switch is used, avoiding the hassle of going out into the field for deployment and service of equipment. Because no splitters or active components are used in the outside plant, new technologies can be accommodated without a major impact on the network topology.
- To keep the costs low, the connection from the subscriber to the access switch is not protected.
- Ethernet-based networks can support all packet-based services including voice, audio/video, and data. A Layer 2 VLAN provides a protocol independent path through the network that can be used to deliver a service to individual subscribers. Subscribers can be



MCM: Media Conversion Module
- Converts optical (100Base-FX) to electrical (100BaseT) Ethernet

MEG: Multi-Services Ethernet Gateway
- Data network functionality
- Optinally managed ports for additional services
- Legacy and media interfaces will become plug-in

TEG: Telephone Ethernet Gateway
- Interface to legacy phone equipment

Figure 3: Generic customer demarcation vision

assigned to multiple VLANs depending on the number of services they purchase. Ethernet VLAN technology is well understood and widely available at low prices. VLANs segregate customer traffic and provide security and quality-ofservice enforcement.
- The IP layer has been added to address scalability issues, to provide IP QoS, to support AAA functions and provide a routed interface to the service provider networks.

Customer demarcation

The interface at the subscriber side should be kept as simple and universal as possible.
Therefore the interface at the subscriber premises will be 10/100BaseT Ethernet over a standard RJ45 connector. An optical/ electrical Ethernet transceiver is the network termination device at the customer premises. Depending on the services that a user has subscribed to, one or more gateway devices may be required; that is, a set-top box for video services and a H.323 telephony gateway for voice service. The 10/ 100BaseT Ethernet interface gives maximum flexibility in the choice of CPE, and avoids up-front investment by the access provider in services-related equipment.
Both media conversion and service gateway functionality may be integrated in a single residential gateway device; however, this solution is less cost-effective when only a subset of the available services are required.
A generic vision to customer demarcation may look as shown in Figure 3.

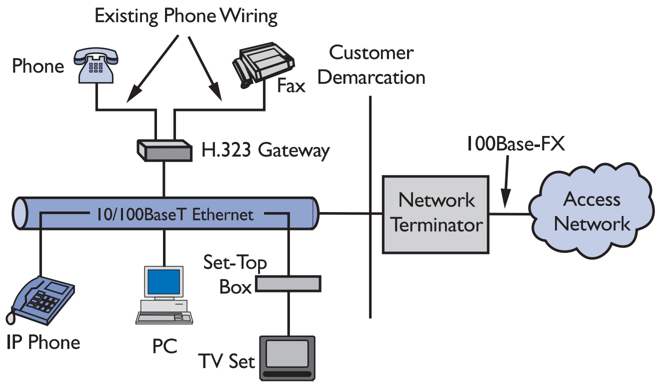


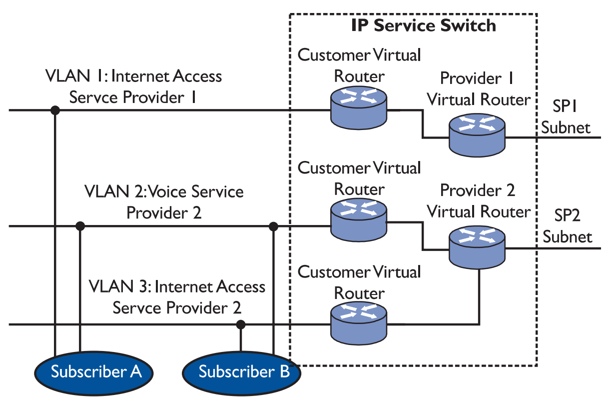
Figure 4: Typical customer premises solution

Figure 4 shows an example of how the situation at the customer premises may look when different gateway devices are used for each individual service.

Design for end-user services delivery

Different service providers, as explained earlier in the section on 'requirements', can offer end-user services on the access network. One service provider may offer a number of services. Each service may be offered with a specific QoS level at the transport layer.
Services like Internet access may be further differentiated at the IP service layer (that is, Bronze, Silver and Gold access) based on user policies.
A VLAN is a virtual Ethernet segment (often referred to as VLAN 'rail') that physical ports on the access switch can be assigned to. A subscriber port is assigned to multiple VLANs which correspond to the services the subscriber has purchased (Figure 5). As an alternative, port-based VLANs can be used where each access port has its own VLAN assigned; however this concept is less scalable.

Figure 5: Use ofVLANs



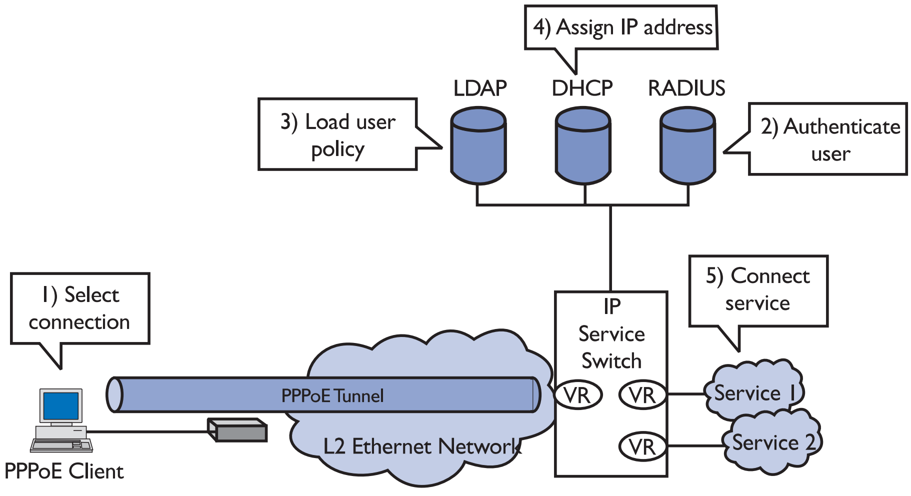


Figure 6: Use of VLAN's

A pure layer 2 solution is ideal for a services-transparent FTTH network. Scalability issues, security issues, and IP QoS issues force us to include an IP service layer in the network. This IP service layer provides the following functions:

- authentication and accounting,
- tunnel termination,
- IP address assignment,
- security,
- bandwidth management,
- IP routing,
- quality of service/class of service enforcement, and
- network address translation (NAT).

The IP service layer can be centralised in an IP service switch or distributed across the network by adding L3 capabilities to the access switches. An IP service switch at the edge of the network scales better and provides more flexibility in accommodating different access methods for different services as will be demonstrated later. This IP service switch implements virtual routers at the interface between the access network and the networks of the service providers (Figure 5).

Each VLAN is assigned to a virtual router at the service layer, called the customer router. This customer router aggregates all traffic for one specific service and service provider. The functions performed by the customer router depend on the specific service, as described below. Traffic from different customer routers, associated with different services provided by the same service provider, is mapped by the provider router to the IP subnet of the service provider.
IP addressing in service provider networks requires careful planning since available address space is usually limited. IP addresses can be dynamically assigned via the IP service switch using an external DHCP server. The IP service switch performs IP routing and NAT. This method makes it possible for service providers to offer services across the FTTH network without changing their addressing schemes or routing architecture.

Internet access and data VPN services

The end-user should be able to select dynamically the IP network (ISP or VPN)
which he/she wants to connect to. IP addressing schemes of different networks should be kept separate. VLANs provide customer traffic segregation at the Ethernet layer, but do not provide sufficient security at the IP layer.
The point-to-point protocol over Ethernet (PPPoE) tunnelling protocol will provide traffic segregation within a VLAN. This protocol is common in DSL networks. No routing at the IP layer is required. The mechanism to establish the PPPoE tunnel includes authentication and authorisation. It allows assignment of IP addresses and network policies by the service provider.
The scenario for establishing a PPPoE connection is shown in Figure 6.

The steps shown represent the standard process of establishing a connection. In step 3 the IP service switch retrieves the parameters (QoS, filtering, etc.) from the LDAP (lightweight directory access protocol) database of service profiles. The IP service

switch should support the dynamic processing of session-level flows by service profiles stored in an external policy server.
Using standard protocols such as RADIUS or LDAP, policy profiles are retrieved from a central database that determines which service processing functions are uniquely applied to each user traffic flow. The dynamic behavior of the IP service switch is controlled by service profiles created in an external server using a service provisioning application. This approach is the key to the scalability of the provisioning model where device configuration is decoupled from service provisioning. All policy-driven devices in the network can share a common set of server-based policies.
Although VPN tunnels effectively segregate user traffic, Ethernet switches act as bridges for traffic with unknown destination. This enables users to create private Ethernet domains based on alternative protocols, consuming bandwidth that is dedicated to FTTH services. Filter capabilities in the access switches, which restrict traffic based on Ethernet MAC addresses, can solve this. However, these filters require careful provisioning by the network provider. A preferable alternative is a filter capability that restricts traffic flows in a specific direction for a specific port (for example, forced egress, which means that incoming traffic of a subscriber port can only exit the Ethernet switch through a trunk port and not through another subscriber port).

Voice services

Voice service requires a VoIP client at the subscriber premises (PC softclient, IP phone or media gateway). The service provider needs a voice gateway (in case of access to a TDM switch) or a softswitch (in case of a pure VoIP network).
Voice is offered on a separate VLAN. The solution allows multiple service providers to offer voice. Each service provider will have a dedicated VLAN for the voice service it offers.
CPE media gateways and IP hardphones will have their IP address assigned by the service provider.
To ensure sufficient QoS is available for voice services, priority queuing mechanisms can be used on the access switches (IEEE 802.1p). In the aggregation network sufficient bandwidth should be reserved for the voice traffic.
Security is not implemented at the transport layer; instead registration and admission control is implemented between VoIP endpoint and the gatekeeper function in the softswitch or voice gateway.

Video and audio distribution

The video and audio services require a settop box at the subscriber premises. As with the voice service, the IP address of the set-top box will be assigned by the service provider.
In traditional video and audio distribution networks all programmes are sent to the subscriber simultaneously. Since this
requires more bandwidth on the access layer than is economically justified, multicasting at the IP service layer can be used to send a single data stream to the access layer instead of multiple data streams per subscriber. Bandwidth requirements can be greatly reduced by replicating the multicast traffic as close as possible to the end-user. Some Ethernet switches are able to recognise IP multicast traffic at the Ethernet layer, effectively increasing multicast performance. The use of multicast clients makes it possible to enhance the service with video on demand, pay per view and delay TV. Because the proposed solution is essentially IP-based, all of these services can be delivered by using readily available video servers, set-top boxes, etc.
As with the other services, a VLAN identification is assigned to each distribution service or video-on-demand service offered by a service provider. Since multicast traffic flows mainly in downstream direction QoS is easier to accomplish by policing the traffic at the IP service layer.

Network operations

The operations and maintenance system has to meet the requirements imposed by the business model, which has been explained in the section on 'network management and customer-relations management'. Procedures to operate and monitor the network should be straightforward and cost-effective. This section describes how this is done for the FTTH network solution presented here.

Service provider operations

For every service provider a virtual router has to be provisioned in the IP service switch, which is connected to the IP subnet of the service provider (referred to as *provider virtual router*). Policies must be defined for the services, which the service provider plans to offer. The RADIUS server, which acts as a proxy to the service provider's authentication server, has to be provisioned with a number of parameters related to the service provider.

Provisioning a service

Provisioning of a service consists of the following actions:

- Create a virtual Ethernet segment for the service and assign a VLAN identifier to the segment.
- Define a customer virtual router in the IP service switch, connect it to the provider virtual router and to the Ethernet segment.
- Define the user policies that apply to the service. These user policies are stored in the LDAP database, which is used by the IP service switch as explained in the section on 'design for end-user services delivery'.

This requires interaction with different management systems: element management systems for the Ethernet switches enhanced with Ethernet network management capabilities, the IP service switch, the LDAP database and RADIUS.

Maintenance

The Ethernet management system should be able to grant access to specific management information for service providers.

Network operations

The required functionality can be provided by a combination of element management systems, fault management systems and performance monitoring systems, which are available on the market.

Subscriber operations

Provisioning

As pointed out in in the section on 'network management and customer-relations management' the provisioning of a specific service for a subscriber should be fully automated.

From the subscriber's perspective the subscription process should be simple. We propose the following scenario.

All subscribers with a physical connection to the FTTH network should have access to a subscription service, a portal web site that gives access to subscription pages from all the service providers who offer services on the network. This requires the creation of an 'open' VLAN that the subscription portal is connected to.

A possible implementation of this subscription service is described below under web-based service selection.

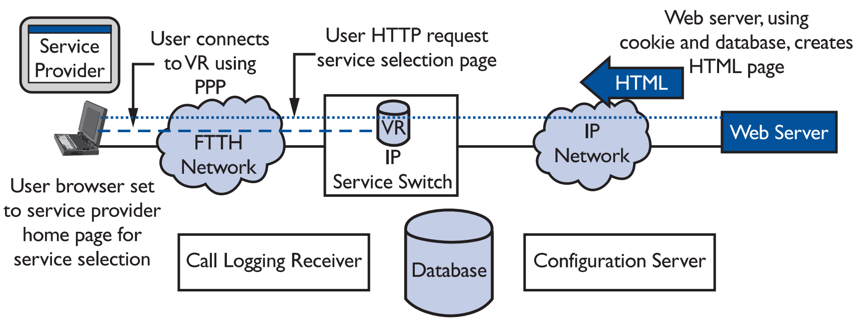
After completion of the subscription process the service provider will have a record that has all the information for the provisioning order to the access network provider, such as the geographical location of the subscriber, as well as the requested services. LDAP is a logical choice for communicating the data between the different systems, because it is widely implemented in both Ethernet switches and IP service nodes.

The provisioning order data can be read from the LDAP database by the network management system of the access network. Once the subscriber is connected to the VLAN corresponding to the requested service, the provisioning tasks for the access provider are completed. The next step would be the authentication process with the service provider, which can also be performed through a web-based interface. The default connection to the subscription portal could also provide a means for the customer to trace the status of his/her order.

The functionality as described cannot be found today in off-the-shelf products, however the underlying protocols and standards like LDAP, CORBA (Common Object Request Broker Architecture) and XML extensible markup language) are widely available. It should therefore be possible to develop the necessary software at relatively low costs.

Services can be packaged with preconfigured CPE equipment, in-house cabling, software and installation instructions.

Figure 7: Customer self-provisioning through web-based service selection



Web-based service selection
A web-based service selection application enables an end-user to subscribe to a specific (set of) service and service provider. The service profiles (policies) are stored in an LDAP database. A RADIUS server can provide AAA functions. The session scenario is explained in Figure 7.

Accounting
The IP service layer is the point where session-level connections are established between users and network services; it's the natural place to perform the fine-grained metering of traffic flows required for usagebased billing. The IP service switch does meter traffic flows using a wide range of billing criteria, and collects information on connections that is exported in detailed accounting records to an external server. This server then translates these records into the appropriate format for the access provider's billing system.

Conclusion

A service-transparent FTTH network can be realised using Ethernet switching technology. Ethernet provides transparent transport with class of service and broadcast/ multicast capabilities at the transport level. This pertains to the connectivity services in the access network. The IP layer provides capabilities needed to deliver the audio/ video/data services in a secure and qualified manner.
The proposed solution supports the business model of an independent access provider. Advantages of the proposed solution are:

- Splitters or active components are not used in the outside plant, therefore new technologies can be accommodated without a major impact on the network topology.
- The 10/100BaseT Ethernet interface at the customer's premises obviates the need for the access provider to invest in services specific CPE. The choice of CPE is in theory unlimited. In practice the service provider, not the access provider, determines the choice of CPE.
- Competitively priced Ethernet technology from the enterprise world is applied in public networks.

Issues that require further work are:

- Unauthorised use of the network-as pointed out earlier features must be added to the Ethernet switches, which prevent traffic between two subscriber ports.
- Automation of network operations-it is imperative that in particular the provisioning activities for individual subscribers are fully automated to keep the operational cost for the access provider as low as possible. In the subsection entitled 'Subscriber operations' on the previous page we indicated a way forward.

Significant effort has been spent by operators and the industry in developing passive optical networks (PONs) as a technology for FTTH. Lucent Technologies has participated in this work with optics research and products for trials and limited field deployment. These point-to-multipoint solutions have the disadvantage of the high cost of the optical/electrical components. PON solutions based on ATM carry the burden of a service-aware customer demarcation. In such a solution the customer demarcation can contribute up to 80% of the cost of the solution. In the solution proposed here, this contribution is 15-20%.
Ethernet PON will give some relief here, but the real break-through of PON technology should be expected when WDM PON is economically viable in the access network.
At present, the costs for PON technology is well above the cost for high performance switched solutions. So, today, 'active' is the way to go in order to provide fully converged voice, video and data services over a single optical network.

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