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The Topological Concept of a Generalized Shield

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ABSTRACT

The electromagnetic shield is generalized to include all surfaces that represent an attenuation of electromagnetic coupling. This concept of a generalized shield has a very important topological significance owing to the one-to-one correspondence between the theoretical topological boundary and the practical boundary between different electromagnetic environments, the generalized shield. The physical understanding of grounding and shielding issues is to a high extent improved by the concept of the generalized shield. By providing an unambiguous definition of ground it promotes a uniform view of grounding. Since all practical shields and grounds are in fact generalized shields, the concept constitutes an essential link between theory and practice. The shielding criterion of a generalized shield is a Maximum Allowed Coupling (*MAC*) that is of general nature and provide a preferable foundation for shielding requirement specifications.

INTRODUCTION

In electromagnetic topology, the topological surfaces represent boundaries separating different electromagnetic environments in different zones. An adequate requirement to impose on such a boundary is a maximum allowed coupling between electric conductors on the opposite sides of the boundary which certainly does not implicate a homogeneous metal shield nor an enclosing shield surface. Sufficient conditions are given by the actual situation; some parts of the generalized shield may have to consist of electrically conducting surfaces, some may not. An acceptable boundary might be a simple net structure or a metallic ground plane. As this boundary, in a topological sense, is equivalent to an impervious shield without having the same local shielding properties along the surface, it is called a generalized shield.

Grounding is given relatively much attention, because the introduction of the generalized shield significantly changes the concept of ground. Grounding is topologically defined as connection to the shield. This condition is universal because all real grounds constitute generalized shields. Certainly, the possibilities to find unified procedures for grounding are improved thanks to the general character of the definition. As a matter of fact, the generalized shield concept has evolved in context with attempts to compose a unified grounding theory.

Each subdiscipline may define its own ground; nevertheless, in the guise of a generalized shield all grounds have to satisfy general topological requirements. When specifying shielding performance, the most common procedure consists of requiring a certain shielding effectiveness, i.e. a material quality of the shield. However, imposing such a requirement on a generalized shield, is obviously meaningless, as coupling mainly occurs independently of the shield material. Realizing that all shields are in practice generalized shields, it is easy to understand that shielding requirements should be focused on the function rather than the material. Consequently the generalized shield concept provides guidelines for specifications by use of the topological boundary requirement, guidelines useful also for low performance shields with a multiplicity of imperfections. If the requirement is defined by coupling parameters, the old problem to find reasonable methods of evaluating a more or less deficient shield no longer exists.

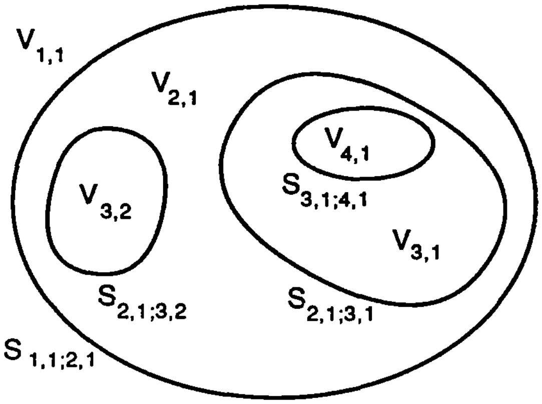
ELECTROMAGNETIC TOPOLOGY

The mathematical formalism and concepts developed since a long time under the name of topology have been proven to be very useful in the theory of electromagnetic compatibility. Electromagnetic interference reduction, EMP hardening, lightning protection and TEMPEST defeating are activities benefiting from the new theory of integrated electromagnetic grounding and shielding based on electromagnetic topology. The basic theory, developed by Carl Baum, is comprehensively presented in [1]. In the field of EMP, a hardening method called *Controlled Electromagnetic Topology* has evolved by contributions of numerous EMP specialists. The generalized shield, the main topic of this report, serves as a link between topological shielding theory and praxis and provides a point of reference for grounding.

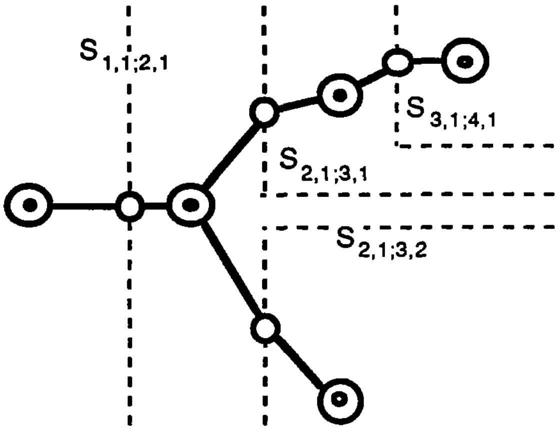
TOPOLOGICAL BOUNDARIES

By using a simplified, popular interpretation, volumes and surfaces of electromagnetic topology may represent shielded compartments, the shield forming the topological surface. Were there apertures in the shield, a closed surface would be conceived, according to intuition, by the covering of all openings with imaginary shields. Large apertures, however, may cause some hesitancy about extending the shield.

TOPOLOGICAL DIAGRAM



INTERACTION SEQUENCE DIAGRAM



Sublayer $\equiv V_{\lambda,\ell}$

Subshield $\equiv S_{\lambda,\ell_1;\lambda,\ell_2}$

- Coupling is given by a supermatrix equation.
- Good shielding approximation simplifies the equation.

TOPOLOGICAL DIAGRAMS illustrate topological properties such as coupling paths and boundaries (subshields) between different zones (sublayers).

A more careful explication shows a somewhat different description of the physical properties of a topological surface which in fact symbolizes a *boundary between different electromagnetic environments*. The crucial electromagnetic quality of a topological surface is its hindrance of electromagnetic coupling, which is logically distinct from shielding. A topological boundary is a surface around a volume containing circuits incapable of coupling to anything outside the volume. This definition readily offers the implication that the boundary may exist without any shield at all. Shielding is simply one of many implements to reduce coupling. Coupling is bounded by a lot of other circumstances such as polarization discrepancy or mere distance. A mathematical way of expressing the non-coupling criterion is defining the boundary as an orthogonality between the actual circuits on the different sides.

MAXIMUM ALLOWED COUPLING

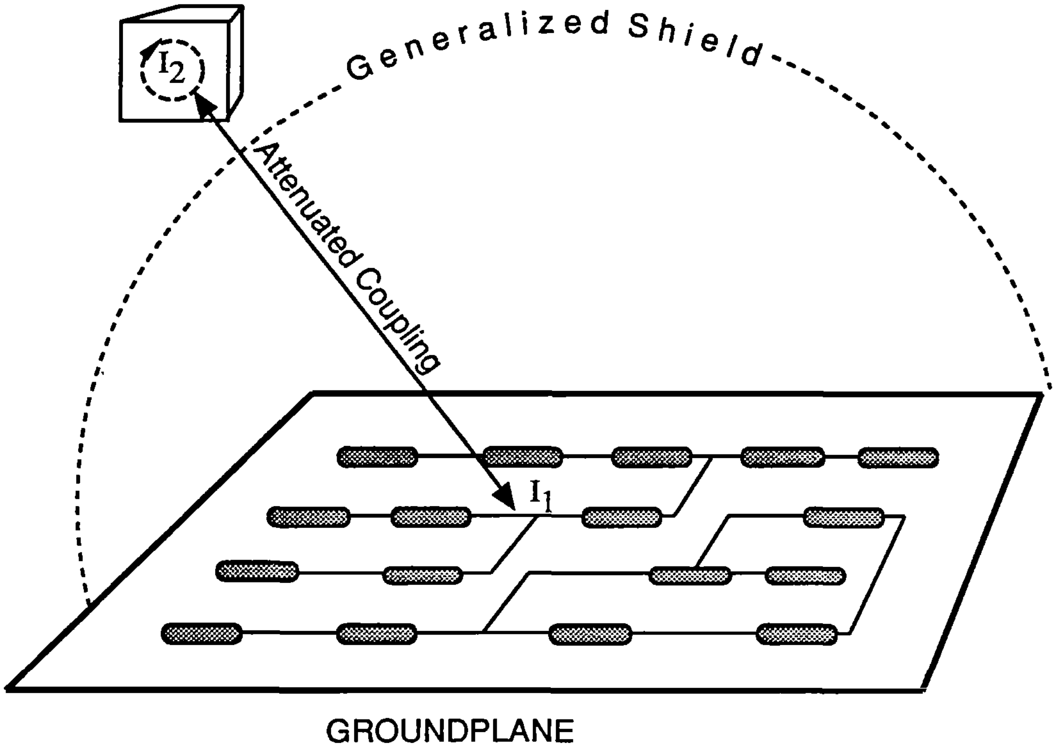
In topology, there is only the question whether coupling does occur or not, the quality of the coupling is not considered. Consequently, a level has to be assigned to each case in order to discriminate between the two states of coupling and non-coupling. In practice, the acceptable level of coupling has to be experimentally determined or assessed. Shielded room specifications must include a requirement of *Maximum Allowed Coupling (MAC)* in order to define design and methods of verification.

GENERALIZED SHIELDS

As described above the topological boundary is characterized by the absence of coupling between the inside and the outside. The corresponding physical boundary we name *Generalized Shield,* which has the quality of representing an attenuation of coupling. Unlike the usual electromagnetic shield, the generalized shield only *represents* attenuation. The attenuation does not have to occur at the shield or even because of shielding.

The generalized shield is of course frequency dependent which may implicate that different topological models are valid at different frequencies. We choose to illustrate the concept of the generalized shield by some practical examples.

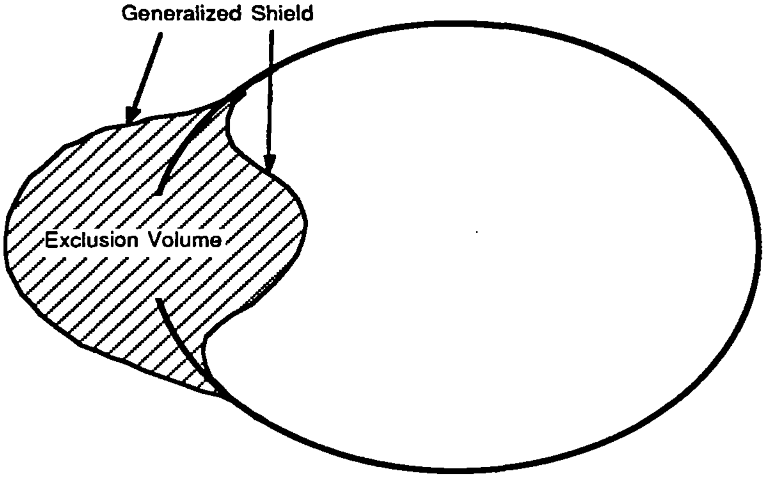
Groundplanes. Metal planes are often used in practice by electronic engineers as shields against electromagnetic interference. The electronic circuits are mainly extended in two dimensions forming a plane with all conductors parallel to the groundplane. Close to the metal surface, the electric field vector is perpendicular to the plane, and therefore coupling to the circuits is reduced, more effectively the closer the circuits get to the groundplane. The generalized shield, which has to be a closed surface corresponding to the topological boundary, coincides with the groundplane all along the surface and continues in the free space enclosing a volume above the groundplane. The volume enclosed should be given such dimensions that emissions from circuits outside the volume do not interfere with those on the groundplane.



GROUNDPLANES are often used in order to reduce the coupling between electronic circuits. The horizontal component of the electric field vector is considerably reduced by the proximity of the plane which decreases the coupling. The location of the surface closing the generalized shield in free space is determined by a criterion of sufficiently low coupling between circuits on the groundplane and circuits outside the generalized shield.

Since no external circuits are allowed in the enclosed volume, there is an incentive to keep the volume as small as possible. Groundplanes compose a very important class of generalized shields suitable in many practical cases of electromagnetic interference protection. The generalized shield concept improves the understanding of interaction between groundplanes; the compulsion to define an imaginary part of the shield supports formulations of EMC criteria.

Shielded Room with Large Aperture. The shielding performance of a shielded room with a large aperture is almost exclusively determined by the coupling through the aperture. Closing the generalized shield is equivalent to closing the aperture because anywhere else the generalized shield coincides with the shield around the room. Obviously, the coupling through the aperture is dependent on the distance between the aperture and the circuits. The position of the generalized shield closing the aperture is determined to vouch for the coupling to be limited below the level of *Maximum Allowed Coupling (MAC).*



EXCLUSION VOLUMES around large apertures close the generalized shield. No electric circuits are allowed in an exclusion volume. The surfaces defining both sides of an exclusion volume are determined by a maximum allowed coupling criterion: Coupling between circuits on different sides of the generalized shield must be below the *MAC* -level.

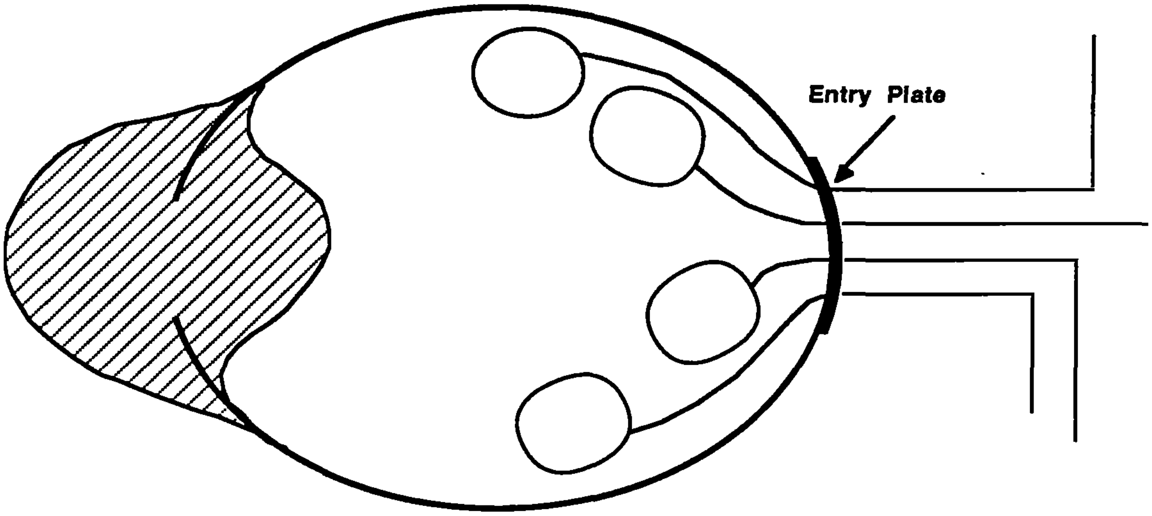
When the wavelength is large compared to aperture dimensions, the coupling decreases monotonously with increasing distance from the aperture. A small enough coupling between circuits is achievable provided both circuits are located outside a sufficiently large volume surrounding the aperture. Defining an exclusion volume around the aperture where no circuits are allowed may be interpreted as assigning a certain thickness of the generalized shield, the two surfaces of the generalized shield thus framing the exclusion volume.

This is an important class of generalized shields because there is often much to be gained by allowing large apertures in shielded rooms without increasing the coupling above the critical *MAC*- level. Special doors with contact fingers are expensive, bulky and heavy to operate and should be installed only if necessary. Windows will considerably improve the work environment in a shielded room and may be feasible if the resulting generalized shield is sufficiently good.

Cabinets connected by a cable tray. A metal cabinet is intuitively easy to imagine as a closed generalized shield. As required by the controlled electromagnetic topology, all electric connections to anything outside the cabinet have to be filtered by the very shield penetration. When there are many connections between two cabinets it may be favourable to fuse both of them into one generalized shield, thereby saving a number of filters. The cabinets must be joined by a conduit or simply by a cable tray. The quality of the cable tray is determined by the *MAC* criterion, i. e. the coupling between the wires in the tray and external circuits have to be below the prescribed upper bound.

Homogeneous shields, forming a certain class of generalized shields, are characterized by an attenuation confined to a surface everywhere coinciding with the topological surface. Since most practical shields, including heavy metal shields, sometimes called "homogeneous shields" have some imperfections or apertures, they should rather not be categorized as homogeneous shields.

All points of entry into the generalized shield have to be controlled with regard to *MAC*. Are there circuits close to an opening and the coupling higher than allowed, a possible measure may be to move the circuits or cover the opening. Cable penetrations should be concentrated to one point of the generalized shield where the shield has a conductivity sufficiently good to connect the penetrating cables in order to divert the parasitic currents. At this point, all penetrators shall have good contact with the shield, shields of shielded cables must be well connected and other cables be connected by means of filters. This important part of the generalized shield is called the *Entry Plate.*



THE ENTRY PLATE provides the important connection between all penetrating cables. Shields of shielded cables are directly connected to the entry plate while unshielded cables are connected by means of filters. Bad connection may cause disastrous currents inside the generalized shield.

REALIZATION OF TOPOLOGICAL BOUNDARIES AND GROUNDING

Controlled Electromagnetic Topology establishes a powerful method in achieving an efficient allocation of hardening measures, such as shielding and filtering, when designing a system required to endure a specified electromagnetic threat. Transforming the topological model into a real, physical structure involves an economic cost versus performance optimization, a process taking into consideration operative advantages of large apertures and budgetary favourable low-quality shields. The knowledge of the most important characteristics of the generalized shield simplifies the formulation of requirements into a cost effective composition.

Analysing a real system in order to assess susceptibility to electromagnetic interference calls for a topological subdivision of the system into different zones, each one possessing its own electromagnetic environment. The task is quite intricate because as a rule no immediately indisputable distribution of topological boundaries is possible to draw up. Thinking in terms of generalized shields may help to disperse the haze.

Certain grounding measures are known to be quite effective in enhancing electromagnetic compatibility, minimizing shock hazards and protecting against lightning. For some reason, however, adequate attention is seldom given to these measures during the design and construction phase of facilities housing electronics complexes, except for the safety requirements imposed by local electric codes. Attempts to compose a unified theory in order to include grounding in the Controlled Electromagnetic Topology, initialized the development of the generalized shield concept. In the following paragraphs the important issue of grounding is treated. Ground is topologically defined as the generalized shield and simple grounding rules are formulated.The usual reluctance to accept new ideas, in most cases due to lack of understanding, may hopefully be vanquished by the simplicity of the definition and the rules of grounding.

A most important question to answer before setting to work with the grounding, is why the grounding should be carried out. Too much grounding has already been accomplished for no real reason, but routine and tradition, or for the wrong reason. There may be more than one reason, for instance personal safety, lightning protection, or EMI reduction, that have to be concatenated into one unified grounding requirement. Once the objective of the desired grounding is clearly understood the way to proceed usually becomes obvious.

EXISTING GROUNDING PRAXIS

Each subdiscipline possesses its own set of grounding rules, one set frequently conflicting with another. Grounding seems to have played an inferior role in EMI control and has been rather nebulously defined which might be the main reason for the difficulty in unifying the different requirements on grounding into a single set of grounding rules. Most grounding seems to be carried out rather according to habit and tradition than topological analyses aiming at achieving adequate and optimal distribution of grounding wires in a balanced EMI protection. Grounding has sometimes got a bad reputation of being a waste of copper, providing an interference distribution network. Correct grounding, however, ought to be considered as an important instrument in Controlled Electromagnetic Topology.

The application of the concept of a generalized shield will enable representatives of different disciplines to avoid incompatible grounding requirements and conflicting grounding practice. As will be shown the generalized shield is the only possible ground,by definition.

SIGNIFICANCE OF GROUNDING

Asking engineers from different disciplines about their conception of grounding may well result in a heterogeneous aggregate of answers. Yet there is a common factor which can be described as a strive for potential equalization. Let us lay down a definition of grounding as being an access to a potential reference. Then the immediate conclusion will emerge that grounding is a comparatively low-frequency phenomenon since the coveted potential reference has to be within a distance much shorter than a wavelength. Otherwise, the potential concept looses its meaning. Thus *grounding is equivalent to connecting to a potential reference* by means of a ground wire. When trying to convey the potential reference to the grounded object, there are primarily two imperfections to overcome. One is the impedance in the grounding wire which becomes less important the less current there is floating on the wire, the other being voltage induced in the grounding circuit from external sources.

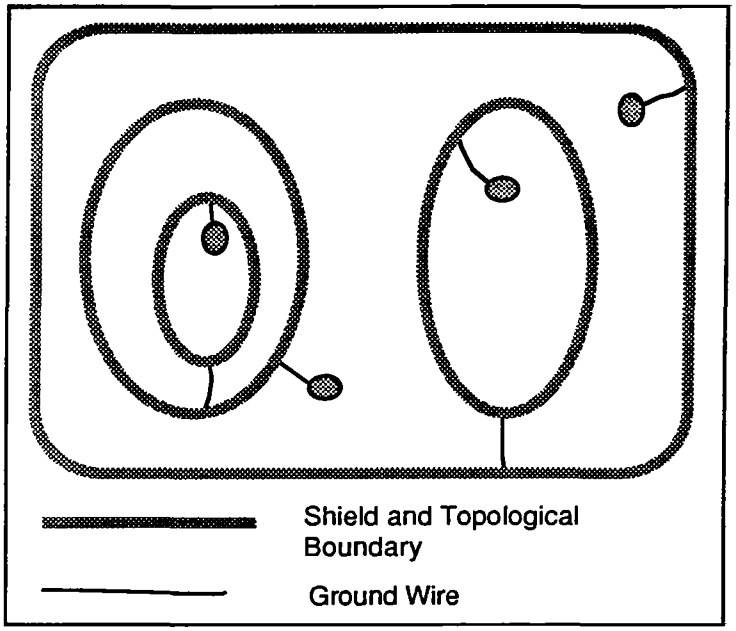
A controlled electromagnetic topology provides an infrastructure that allows of a rigid definition of grounding which is electromagnetically correct and unassailable. Within a topological volume surrounded by a closed shield *grounding is identical to connecting to the shield.* This topologically valid definition of grounding is given by Carl Baum in [2].

GROUNDING IS CONNECTING TO THE SHIELD

It is obvious that the shield provides an unambiguous potential reference in the volume at frequencies with wavelengths much greater than the linear dimensions of the shield. At higher frequencies the potential reference has to be confined to certain subvolumes defined by generalized shields as described in the following. Once the definition is stated, three fundamental rules for grounding are formulated:

- Ground is defined as the shield.
- Grounding is allowed within the zone only.
- Ground wires must be much shorter than a wavelength and have negligible impedance.

The first rule simply expresses the definition and needs no further comment. The potential measured outside the shield has no meaning within the zone, thus entailing the second rule. Although this rule is close to a truism in electromagnetic topology, it seems to be useful in practice where grounding is sometimes ordained to be an "absolute earth potential". If such a prescription, however meaningless, has to be obeyed, the shield can be connected to this external reference on the outside. The third rule is a reminder that the ground wire is expected to transfer a potential reference calling for as good as constant potential along the whole wire.



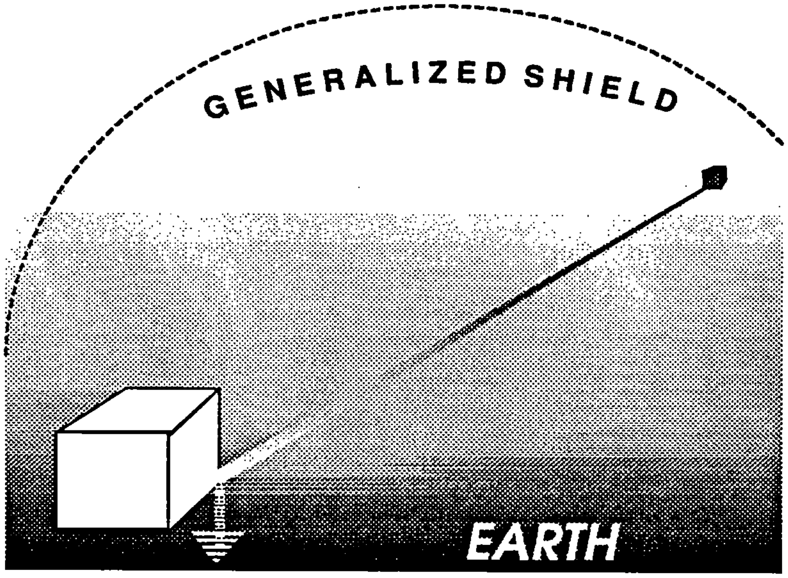
GROUNDING is defined as connecting to the shield within the zone as illustrated in the figure. No adequate grounding outside the shield is possible because the shield represents the natural potential reference. The topological boundaries correspond to generalized shields. Parts of the generalized shields must consist of conductive materiel to be able to serve as ground.

The shield is important to grounding for two reasons: It provides a ground reference being the most natural common reference in the shielded volume, and it shields the ground connection thus protecting the grounding from external interference. Obviously, no grounding can be done without a shield, which portends a severe restraint for practical applications. Fortunately, the generalized shield always exists when grounding is possible and the generalized shield assumes the important roles of ground reference and interference protection.

GROUNDING IN PRACTICE DEMANDS A GENERALIZED SHIELD

In a strictly controlled electromagnetic topology, the simple grounding rules advise the procedure of correct grounding. In practice, however, an integral shield around the topological volume may not be necessary to achieve the required level of protection, which makes the topological grounding rules difficult to apply. Or, in other words, there are often irremissible grounding requirements but evidently no shield to connect to. There is an unconformity between theory and praxis implying that topological grounding rules are of limited aid to a practically oriented engineer in his efforts to solve grounding problems. Rather than changing the promising definition and rules of grounding, however, it appears advantageous to generalize the shield and to narrow the gap between the theoretical topological boundary and practical shields. The introduction of the new generalized shield concept, provides a precise correspondence between theoretical and practical boundaries. Furthermore, it forces the engineer to see the ground as a shield also in cases where the generalized shield is difficult to locate.

At very low frequencies, the earth may be considered as a generalized shield. Coupling to horizontal lines above ground will be reduced by the shielding. In the zone defined by this generalized shield, grounding to the earth is meaningful. Or more precisely, *grounding to the earth is possible in this zone only.*



EARTHING by means of ground rods etcetera is meaningful only within a generalized shield in which the earth is constituting part of the closed surface. Such a generalized shield is effective for very low frequencies only.

GROUNDING TO A GENERALIZED SHIELD

In a practical case, grounding means that for some reason one point in an object shall connect to a ground reference. There are two problems to be solved; one is finding the correct ground reference, the other is organizing an access to the reference. Finding the ground reference is sometimes more difficult than it may appear at a first glance. Actually, in some cases there does not even exist a ground reference.

Finding Ground

The first task is to locate the generalized shield. Remembering the definition of the generalized shield being a topological boundary enclosing an electromagnetic environment, a closed surface may be imagined through which coupling is bounded. With the exception of some simple cases where the generalized shield is relatively apparent like chassis, racks, or metal boxes, intuition and creativity will simplify matters. Adjacent zones with their individual environments have to be taken into consideration. It is important that the surface should be completely closed, no part of a system belonging to an adjacent zone must be allowed inside the generalized shield. When two adjacent systems are too close, the solution may be to incorporate both in one common generalized shield. If some communication has to penetrate the shield, there must be a bound for the coupling also this way, often implying filters at the penetration point.

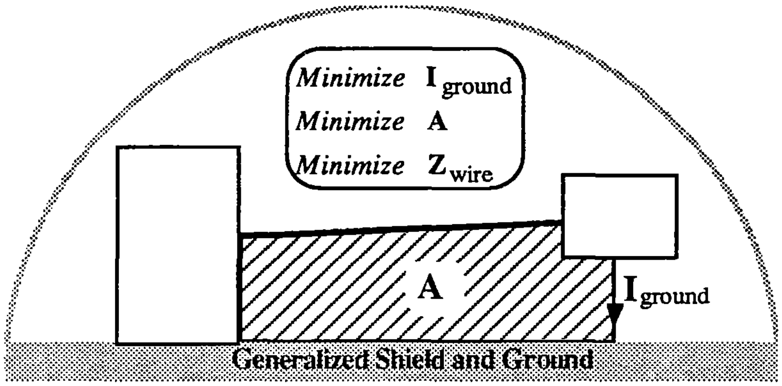
As described earlier, there should be an entrance plate in all generalized shields through which the penetrations are taken. In some cases, the generalized shield is inconceivable because many systems are integrated and balanced together. It must be confessed that a controlled electromagnetic topology is not always necessary for a good function, but hardening such a balanced construction will probably be an impossible mission. Some changes to the physical situation may be helpful in forming the topological boundary.

Bonding metal structures, rerouting cables and installing filters and even an entrance plate may improve the possibilities to define a generalized shield.

When the localization of the generalized shield is found, perhaps after some rearrangement, the point of ground reference has to be determined. For several reasons the most natural point is the entrance plate. There is sufficient conductivity in the shield and there are the best conditions of creating a preferable tree-formed grounding network which will be discussed in the next chapter.

Grounding

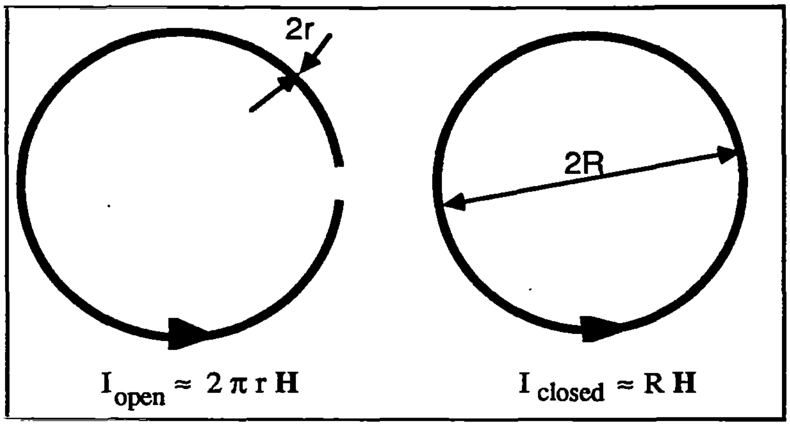
Having defined the ground, the next action will concern the grounding of the object. The procedure may be as simple as connecting the object via a grounding wire the shortest possible way to the ground, but there may as well be complications. We assume the distance between the object and the ground being much less than a wavelength, otherwise grounding is not achievable in this zone. Still, there is a possibility to look for a smaller zone around the object and a corresponding generalized shield to which grounding is meaningful. The grounding wire is intended to transfer the ground potential to the object. There is always an expressed or implicit grounding quality requirement implying that the deviation from the ideally transferred ground potential must be less than a certain voltage which, in general, is a function of frequency. Expressed in another way, the line integral of the electric field along the wire must be less than a certain maximum allowed voltage.



EFFECTIVE GROUNDING requires a negligible potential difference along the ground wire. The ground loop of area A, which is formed by signal cables, ground wire and ground, should be kept small in order to reduce the induced current in the ground wire.

There are in principle two measures to control the voltage deviation in the grounding wire. One is to shield off the external interference fields in order to limit the induced current, the other is to bring about low impedance in the grounding circuit, minimizing the voltage drop produced by parasitic current. It is important to know the generalized shield in order to get as much shielding as possible. Good shielding, which is equivalent to reduced coupling, is achieved by avoiding areas around apertures and routing the grounding wire close to the shield. Accomplishing the low impedance grounding circuit is chiefly a matter of minimizing the length of the wire thus reducing the inductance. The resistive part of the impedance is almost always relatively simple to make negligibly small.

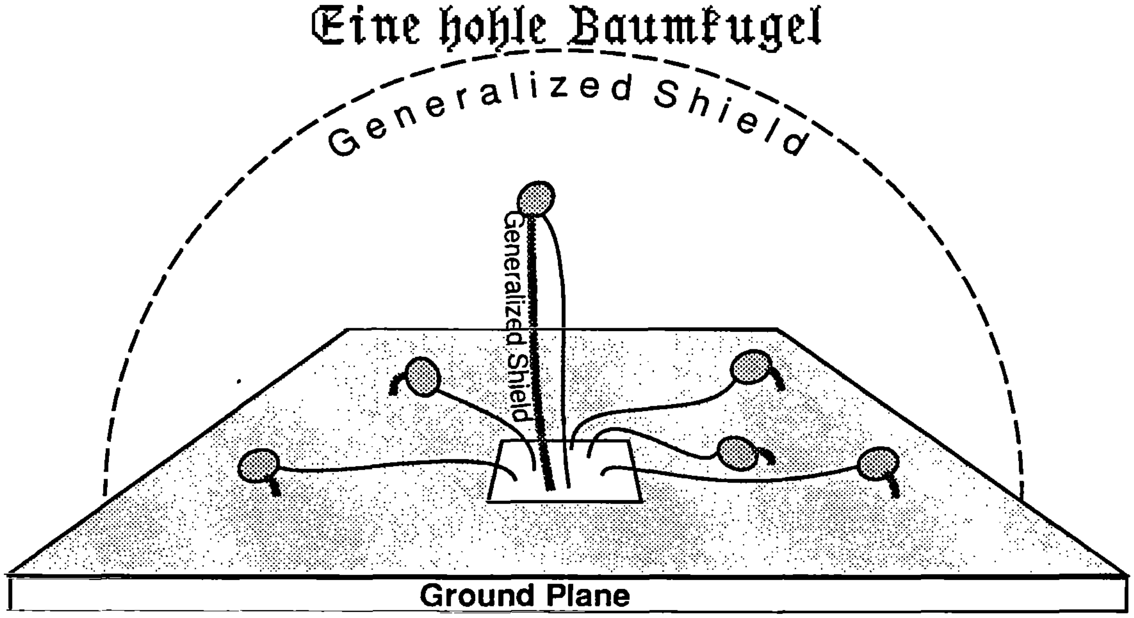
The frequency range in which effective grounding is required must be carefully considered when designing the grounding structure. In effect, the frequency range influences the definition of the generalized shield to a high extent, framing the fundamental condition to attain meaningful grounding. Theoretically, an object may have different ground references at different frequencies so there may be many groundings of a single object functioning at separate frequencies.



INDUCED CURRENT from a low frequency magnetic field in an open loop will increase by orders of magnitude if the loop is closed. Low frequency approximations have been used to derive the expressions for the currents given in the figure.

GROUNDING NETWORKS

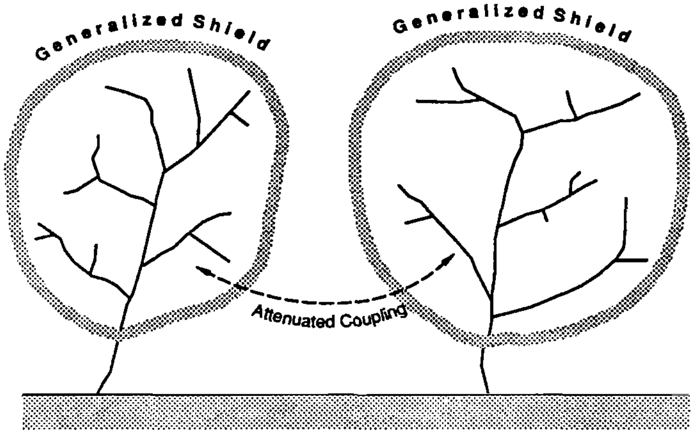
Assuming dimensions much shorter than a wavelength, current induced in a wire from a distant source is in the first approximation proportional to the circumference of the wire. If the wire is bent to form a closed loop the current will increase and assume a value approximately proportional to the radius of the loop. Since the radius of a loop is usually much longer than the circumference of the wire, much larger induced current amplitudes will be found on loop structures than on open wires.



EINE HOHLE BAUMKUGEL is a topological expression for a body topologically equivalent to a hollow sphere. A generalized shield including tree grounding structures is an example of such a body.

It is important to control all possible ways of reducing interfering voltages in the grounding circuits. The impedance in the grounding circuit has to be kept as low as possible in order to mitigate the detriment from the induced current. The importance of limiting the induced current by clever shielding has been discussed in the preceding chapter. Avoiding loops when designing the internal grounding network in each zone will considerably reduce the induced current. The grounding network should form a tree or, by a topological expression, a body called *Baumkugel* (coined in [2]). Some loops are not possible to avoid, for instance those formed by shielded cables. The interference can be controlled by minimizing the loop areas, bundling the cables and locating the bundle close to the generalized shield. Attempts to stop the current by breaking the shield, as erroneously advised in some EMC-literature, will result in worse interference. So called multipoint grounding should be conceptualized as a method of forming loops to improve the generalized shield, providing good ground reference and shield for the internal ground network.

Very low frequency grounding praxis developed by long industrial experience suggests a grounding structure in the shape of a number of trees. The trees are isolated from each other except at the roots where they are connected. As a matter of fact, those trees are nothing but generalized shields, each tree forming a topological volume. The recommended grounding praxis complies completely with the grounding rules given here.



TREE GROUND NETWORKS provide structures without ground loops in order to reduce induced currents in ground wires. Coupling between different trees is often avoided by employing isolated coupling elements utilizing fiber optics. Each tree represents a generalized shield.

Applying the idea of a generalized shield gives a foundation for understanding the tree grounding procedure designed for the processing industry. All cables have to follow the tree structure and must not take short cuts between branches simply because they must not penetrate the generalized shield. If two trees get too close, the coupling between the zones becomes too good, the isolation is not maintained but the cure is easily found by means of the generalized shield concept. A new zone has to be formed by fusion of the two trees, the common generalized shield may need some improvement to be sufficiently good and one entry plate must be arranged instead of the original two.

SHIELDING SPECIFICATION

The functional quality criterion on shielding used for generalized shields will be profitable to incorporate in shielding specifications. A clever specification of the shielding performance when constructing shield rooms will probably save considerable cost. The user is interested in an assured function by controlling parasitic coupling. The better the coupling situation is known and can be described, the better the generalized shield will be adapted to reduce the coupling. In the specification, a coupling model should be defined as well as a level for the *Maximum Allowed Coupling* (MAC). Increasing a future flexibility, the coupling model can also be designed to be a worst case such as coupling between the largest possible loop inside the generalized shield and a parallel loop on the outside.

Shielding effectiveness, an often used or rather misused term in shielding specifications, describes shielding capacity in terms of attenuating electromagnetic fields. In the case of a homogeneous shield, it may be well defined as an amplitude ratio between transmitted and incident electromagnetic waves, but using shielding effectiveness as a standard for a shielded room is a blunder. Most shielded rooms must not be considered as homogeneous shields because the shielding capability is mainly determined by the amount of coupling that occurs at certain points of entry, weak spots in the shield. Accordingly they are best characterized as generalized shields with maximum allowed coupling as a quality criterion. Undoubtedly, future standards will specify a *MAC*-level in a coupling model like the parallel loops suggested or some more sophisticated development.

SHIELDING VERIFICATION

In order to verify the shielding capability of a generalized shield, the coupling model given in the specification should be materialized. The coupling is then measured and compared to the required limitation given by the specified MAC. As is evident, the verification of a generalized shield is principally uncomplicated when the coupling model is given. If not, an analysis of the coupling through the boundary must be included in the verification process. Certain general coupling analyses methods taking the worst realistic cases of coupling into account may be helpful. Such verification methods are under development and may eventually be formulated in standards for shielding verification.

There are several methods, carefully prescribed in standards, which are designed to measure shielding effectiveness. These methods are not useful in determining an upper bound of coupling, verifying that the MAC is not exceeded. The result, when applying such a method on a generalized shield, is the very coupling between two circuits of the kind specified for the method. This coupling situation is impossible to generalize into the actual model or a worst case model. If the shield material is known, the result from measuring on a homogeneous shield will only give the thickness of the wall.

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