

INVESTIGATION OF CONVENTIONAL SIGNAL COMBINING TECHNIQUES IN SHORTWAVE SPATIAL DIVERSITY RECEPTION TECHNOLOGY**KONVENCIONÁLIS JELKOMBINÁCIÓS ELJÁRÁSOK VIZSGÁLATA A RÖVIDHULLÁMÚ TÉR DIVERZITATI TECHNOLÓGIÁBAN**KOVÁCS Róbert¹**Abstract**

My research explores the potential of diversity reception technology and the signal combination techniques that can be used in its methodology. In the first part, I describe the historical development of diversity reception and its methodological possibilities. Within this, I focus on the study of relevant diversity procedures. By means of an analytical comparison of a conventional group of signal combination procedures, I illustrate their specific capabilities. I describe the signal-to-noise ratio based utility capabilities of conventional signal combination procedures. Finally, I provide applicable recommendations for the selection of SC, EGC and MRC signal combining procedures based on my simulation results.

Keywords

diversity reception, signal combining methods, SNR signal-to-noise ratio improvement, multi-band reception systems, SC, EGC, MRC signal combining methods

Absztrakt

Kutatásom a diverziti vételtechnológia és annak módszerében alkalmazható jelkombinációs eljárások hasznosíthatósági lehetőségét vizsgálja. Az első részben ismertetem a diverziti vétel történeti fejlődését és vizsgálati módszertani lehetőségeit. Ezen belül fókuszálok a releváns diverziti eljárások tanulmányozására. A jelkombinációs eljárások konvencionális csoportjának elemző összehasonlításával bemutatom azok egyedi képességeit. Ismertetem a konvencionális jelkombinálási eljárások jelzaj viszony alapú hasznosíthatósági képességeit. Végül szimulációs eredményeim alapján alkalmazható ajánlást adok az SC, EGC és MRC jelközösítési eljárások megválasztásához.

Kulcsszavak

diverziti vétel, jelkombinálási módszerek, SNR jelzaj viszony érték javítása, többantennás vételi rendszerek, SC, EGC, MRC jelközösítési eljárások

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DIVERSITY RECEPTION TECHNOLOGY

„As the development of radio communication technology began to offer solutions for long-wave and later short-wave links, the discovery and study of propagation anomalies in the short-wave band became inevitable. The recognition of the phenomenon of fading and its spatial, temporal and polarisation-dependent behaviour, paved the way for the development of a reception technique using several simultaneous reception branches and their combinations, called "diversity" to improve the quality of the received signal. [1]

The historical development of diversity receiving

The first actual diversity reception was carried out by two RCA2 engineers. Harold Henry Beverage and H.O Peterson, who in the 1920s used empirical methods to test the possibility of simultaneous, parallel reception of a given radio transmitter signal at two different locations in the 1920s. As a result, they found that the signals received at the two sites had different fading properties, thus giving the bases for spatial diversity reception theory [2], [3], [4], [5]

Later, they developed the first long-range, reliable radio receiver system, patented as RCA DRS, consisting first of two and later of three separate receivers. [6] [7]

In the mid-1930s, Dr. James M. B. Hard developed the XE1G receiver, the first to use a chain-driven tuning system to cover the entire 1.7-30 MHz HF range in four sub-bands. [8]

It is necessary to mention that, in addition to the above, there had been other attempts to create a diversity receiver. In the September 1939 issue of QST, S. Gordon Taylor presented the results of a reception experiment based on the combined use of a Hallicrafters SX-17 and Skyrider 5-10 receivers. [9]

Shortly after this article was published, Hallicrafters' chief engineer Karl W. Miles built the first dual-diversion receiver (DD-1). This unit deployed several modifications thanks to further innovations, which resulted in a total of around 125 production units in two series. [10] [11] [12]

Since the early 1950s, CRC has also been producing mass-produced solutions for frequency-domain diversity. [13]

The emergence and rapid development of semiconductor technology gave rise to more smaller and mass-producible receivers, which could be considered as the predecessors of the later receivers with multiple input channels.

This technological change has also led to a new impetus in theoretical research in the second half of the last century. New scientific results appeared such as a generalised deterministic description of the field spectrum in single and multi-element receiver structures in coherent and multipath propagation environments. [14]

In the new services of the digital era, the use of diversity reception has already become a basic element in mobile technologies using complex digital modulations, mainly in the higher UHF and SHF frequency bands.

Methodological approaches to diversity assessments

The purpose of diversity reception is basically to improve the reliability and quality of analogue or digital signal transmission on radio channels. There are several methods

² RCA: Radio Corporation of America

available to achieve this, the common feature of which is that the signal transmission on the different reception paths is treated as a separate, individual channel with its fading, interference and other characteristics. The conceptual basis for diversity reception is the assumption that the probability of simultaneous deep fading on multiple transmission channels, which can be considered independent and statistically in small extent. [15] [16]

Channel isolation can be implemented in different domains such as space, frequency, phase, time, polarization, angle of incidence or digital signals and even in modulation and code spacing. There are several literature sources available for the definition and (partial) classification of (some) types of diversity reception (e.g., [17] [18] [19] [20] [21] [22] [23] [24] [25]).

Diversity methods can be grouped in several ways. The most common approach is to perform some range analysis of the isolated signals passing through the fading channel. In my research, by processing the literature sources, I found that a significant amount of research material on 21st-century diversity reception methods is available, but it reflects only frequency band, technology and service-specific research approaches. There is no comprehensive source available that provides a complete systematic and comparative analysis. To achieve my research objectives, I considered it necessary to provide a gap analysis that summarises a general conceptual framework for diversity communication technologies and modes in a structured structural framework, taking a band-independent approach. A summary of this gap-filling work, based on a considerably broader source processing than the one in a thematic overview and classification of some types was elaborated and published in my paper "Diversity Reception in Radiocommunication Links". [26]

It is necessary to note that in some cases the content features of diversity classes have some overlapping, and therefore a perfect, all-feature, perpetual, exact conceptual classification, in which each diversity class category has exclusive features, is not feasible. The graphical result of the research work is illustrated in Figure 1.

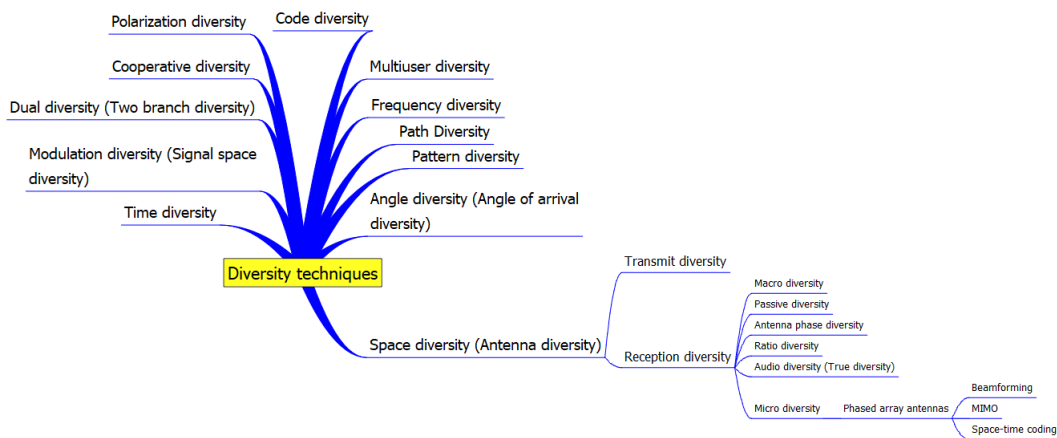


Figure 1. System of diversity receiving methods Source: Edited by the author

In the linked article, I have reviewed the types and categories identified in my research in the scientific literature. The sources are limited and mainly only available for modern mobile technologies (4G, WiFi, WIMAX, MIMO), which practically only approach diversity channel properties from the reception side. In order to fill this gap, I therefore found it

justified and appropriate to recommend the creation of an aggregate terminology system. For many of the diversity methods in strategic data retrieval systems, their application is not possible or it is only possible with significant limitations, since the following boundary conditions have to be considered:

- the radio source to be detected is unique and of unknown geographical location at the time of detection;
- the strategic (or even tactical) reception system has no control over the variation of the transmission characteristics;
- the reception polarisation must be the same as the polarisation of the broadcast transmission (in the case of a single transmitter, this can only be one type);
- in the short-wave range, the $\lambda/2$ half-wavelength is originated from 4.5-5 m even at the very top of the range, and about 40 m at lower frequencies;
- although the characteristics of the bandwidth range make it possible to effectively apply advanced modulation schemes such as those already widely used in other technologies in the VHF and microwave bands, the wavelength size limits the applicability of some of these;
- As a consequence, only a limited range of diversity methods can be used to develop RH radio reception techniques in the shortwave band.

RELEVANT DIVERSITY PROCEDURES

Given the variety of diversity options presented in the previous section, I will only discuss in detail the classes that are relevant to the research topic. These can basically be classified into the larger group of spatial diversities and other categories.

Spatial diversity method

The most common - and perhaps the simplest - way to create diversity receiver branches is a process called space or antenna diversity. By basic definition, this is a radio reception technique in which two or more receiving antennas, spaced a few wavelengths apart, feed individual receivers and combine the output signals of the receivers using some technique. An appropriately chosen antenna spacing ensures that the signals received on the receiver branches are considered uncorrelated. The receiver branches have different fading properties due to varying propagation characteristics and propagation path lengths, but the resulting output signal of the system will have improved and time-varying transmission characteristics. [27]

Using a deterministic description method, it can be shown that:

- System performance improves as the separation distance D of the receiver sites increases;
- A two-element receiving arrangement results in better receiving performance under the assumption of nearly the same angle of incidence, if

$$D \geq \frac{\lambda}{B} \quad (1)$$

- is satisfied, where B is the bandwidth of the stochastic signal, which can be considered random, in any multipath propagation environment;

- the diversity gain decreases as the phase shift increases due to multipath propagation;
- the diversity gain decreases as a function of the increase in the energy of the signal propagating in the propagation path suffering a delay;
- assuming single-path propagation, a system with two receiver sites has a higher return compared to a single-receiver system than the incremental return of any multi-receiver system with the addition of additional receiver sites;
- reception methods that handle both multiple reception sites and multipath propagation (space-time diversity) yield additional gains. [14]

The minimum distance between the antennas of the receivers at a given reception frequency should be about $\lambda/2$. For a value lower than this, negative effects of other diversity mechanisms occur. For larger antenna separation, the multipath propagation channels are considered to be completely uncorrelated, and therefore the probability of deep fading decreases significantly with increasing antenna separation. [17] [20]

However, it should be noted, that there are also scientific approaches, other than the deterministic description, in which the complete independence of the reception channels is only

$$D > 10\lambda \quad (2)$$

is considered real if the condition is met. [28]

If the distance between the receiving sites is in the order of λ , we speak about microdiversity, if the distance is a multiple of λ , we speak about macro- or site-diversity.

For my investigations, it is also necessary to mention the method of baseband or real diversity, in which the outgoing baseband signals of the receiving branches are combined and processed according to some method. The practical testing and analysis of the latter method in real-time measurements were part of my research.

Other applicable types of diversity

It is important to note that the beam diversity used, mainly for phase-driven antenna systems, can be considered a variant of microdiversity if the elements of the antenna array are considered individual receiving antennas. [19]

A further important finding for my research is that the use of beam diversity with separate, isolated antennas can be considered a sub-variant of macro-diversity (this option is not shown in the summary figure). Furthermore, MIMO technology can also be considered as a type of both transmitter and receiver diversity. The latter technology has been able to become a cost-effective and widely deployed component of systems mainly in the higher frequency bands (VHF, UHF). But it should be noted that research is also underway in the HF band to investigate the effectiveness of diversity reception on two-dimensional grid-based antenna systems. [29]

Scattering diversity is also an applicable method for multi-sensor data acquisition systems, provided that antennas with different directional characteristics are used at the receiving points. In this case, the signals received by the antennas will belong to different input directions, thus ensuring the uncorrelated assumption of the received signals from each branch. Scattering diversity is never used on its own but is usually used as a complement to spatial diversity. [30]

ANALYSIS OF THE TRANSMISSION CHARACTERISTICS OF SIGNAL COMBINATION PROCEDURES

The mathematical description and practical realisation of diversity processes are possible by using the so-called signal combination methods. The aim is to combine the received signals with different channel characteristics on each receive branch, based on some algorithm, to produce a resulting output signal with better quality characteristics than if only one receiver branch were available. (Figure 2.)

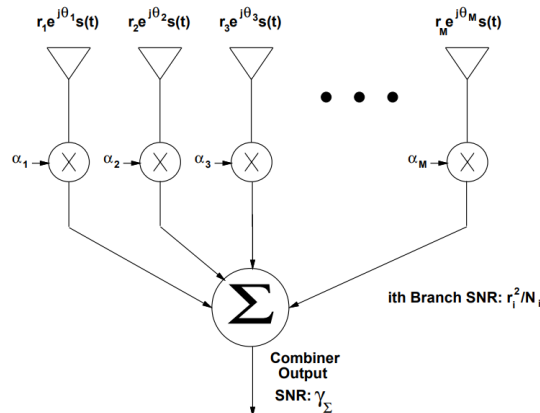


Figure 2. Scheme of linear diversity signal reception Source: [30], [31] (Accessed: 01.10.2022.)

In the linear description approach, we are talking about a rule-based summation/time-based selection of essentially coherent information channels, but the signal selection method and its input parameters differ in each approach. As a consequence, the technological and practical implementation of each method requires a different level of complexity and deployment of the equipment, thus determining the necessary financial backing of the technology. The description of the signal combining approach requires that the fading relations of the individual branches are considered independent, the signals of the channels uncorrelated. The signal combination methods can basically be divided into two major categories, namely the family of Conventional signal combinations and the heuristic approach, which is based on some (e.g. Evolutionary) algorithm.

CONVENTIONAL SIGNAL COMBINING PROCEDURES

A general common feature of conventional signal selection methods is that, among the signals of the incoming signal channels, the branch is selected for output that has some characteristic that satisfies the instantaneous conditions of a decision algorithm built into the combinatorial algorithm. The decision value may depend, for example, on the current value of some feature of the incoming signals, a predefined feature threshold, or a leverage decision threshold calculated from the foregoing. In the case of variants requiring a feature change, the decision conditions may be met by actively modifying the incoming signals individually.

Selection Combining

In Selection Combining (SC), the signal combiner selects the branch with the highest $SNRr_i^2/N_i$ for output. (Figure 3.)

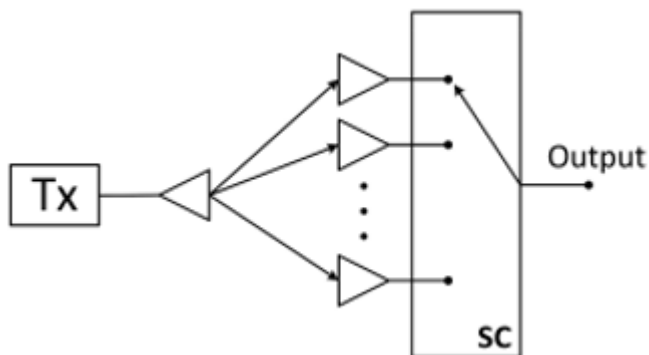


Figure 3. SC Selection combining procedure block diagram
Source: [32], (Accessed: 01.10.2022.)

The principle is equivalent to choosing the branch with the largest $r_i^2 + N_i$, assuming $N_i = N$ noise power on each branch. Since only one input branch is selected for output at a time, the SC procedure often requires only one receiver to be connected to the currently active input branch. However, in continuous-mode transmission systems, each antenna branch requires a dedicated receiver/probe to measure the SNR of each channel simultaneously and continuously. By using the SC signal selector, the current SNR_{out} output signal-to-noise ratio value will correspond to the maximum of the input SNR values:

$$SNR_{out} = \max(SNR_i) \tag{3}$$

Since only one input branch is switched to the output at a time, no phase equalization of the input branches is required, making the signal selection method suitable for use in transmission systems with both coherent and differential modulation. For M branch diversity γ_Σ ³:

$$P_{\gamma_\Sigma}(\gamma) = p(\gamma_\Sigma < \gamma) = \prod_{i=1}^M p(\gamma_i < \gamma) \tag{4}$$

Assuming an uncorrelated Rayleigh fading amplitude distribution r_i on each of the input M branches and defining the average signal-to-noise ratio on the i-th branch as $\bar{\gamma}_i = E[\gamma_i]$ - the SNR distribution will be exponential:

$$(\gamma_i) = \frac{1}{\bar{\gamma}_i} e^{-\gamma_i/\bar{\gamma}_i} p \tag{5}$$

If the average SNR value is the same on all branches $\bar{\gamma}_i = \bar{\gamma}$, the average output signal-to-noise ratio value:

$$\bar{\gamma}_\Sigma = \bar{\gamma} \sum_{i=1}^M \frac{1}{i} \cong \bar{\gamma} \left(C - \ln M + \frac{1}{2M} \right) \tag{6}$$

where C is the Euler constant (the approximation is valid for $M \geq 3$). [33]

³ γ_Σ : The value of the resulting common output signal-to-noise ratio.

Note that even if a Rayleigh distributed fading signal is computed on each of the inputs, the output signal of the signal combiner will not be Rayleigh distributed.

The SC method is the simplest combining method, where the selector always selects the signal of the receiving branch with the best instantaneous quality characteristic - typically the best instantaneous SNR - for output. In principle, since only one branch is selected at a time, the reception of multiple branches could be achieved by connecting a single receiver input. However, if a continuous, coherent signal stream is required at the output - transmission systems, transmission channels using digital modulation, always require this - then to measure the instantaneous SNR of the receive branches, it is necessary to provide a unique receive function on each of the branches. (Figure 4.)

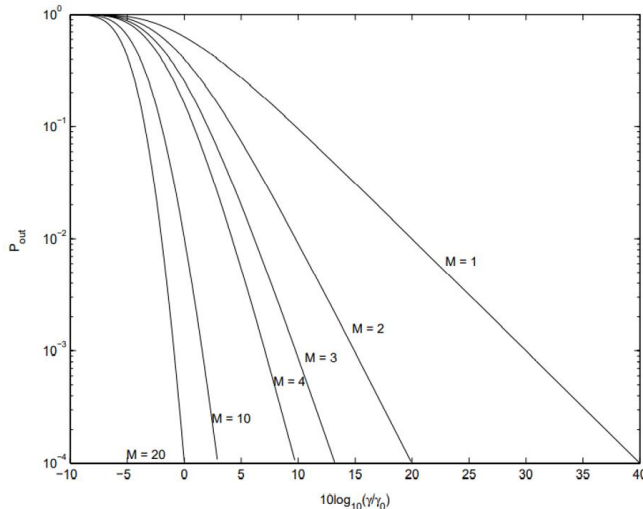


Figure 4. Outage Probability of Selection Combining in Rayleigh Fading
Source: [32], (Accessed: 01.10.2022.)

The maximum of the best instantaneous SNR value achievable in this procedure corresponds to the quality of the branch with the best instantaneous SNR at that time.

From the above, it can be seen that the average SNR gain increases with the number of branches M , but not linearly. Switching from one to two channels yields significantly more gain than increasing the number of branches from two to three. However, further increasing the number of branches yields less and less return, i.e., in general, the average output relative SNR growth fraction decreases dramatically as the number of receive channels increases. [34] [35] [36]

Switching or Switch and Stay Combining

In an SSC continuous-signal system, dedicated receivers are required for each channel to monitor the instantaneous SNR of each branch. The basic TC Threshold Combining method addresses the need for multiplexed receivers per channel since in this case the signal-to-noise ratio of each branch is determined by sequentially polling each branch in a cyclic manner. (Figure 5.)

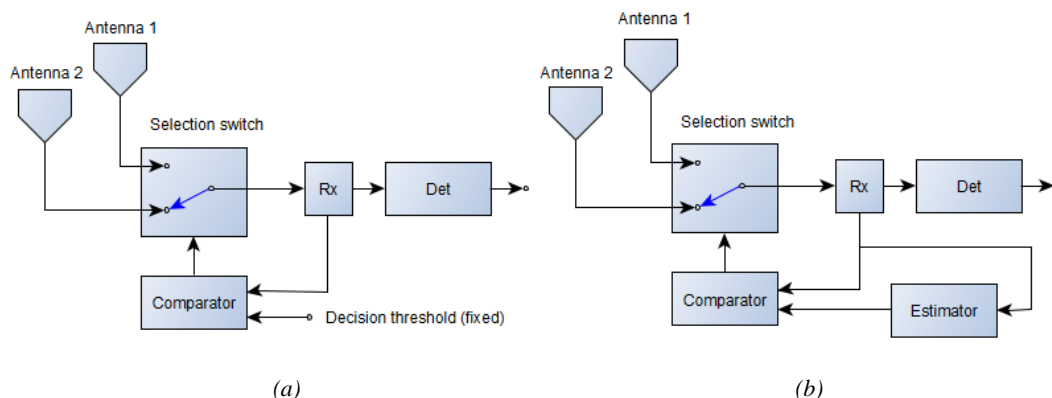


Figure 5. SSC procedure system structure fixed (a) and variable (b) threshold
 Source: Edited by the author based on [34],

The output is the signal of the channel whose SNR exceeds the threshold of a given γ_T for the first time. As in the SC method, no phase equalisation of the channels is required. If the SNR of the selected branch signal falls below the threshold level, the signal selector selects another branch for output that is more favourable than the threshold SNR. The selection can be based on a number of criteria, the simplest of which is random selection.

For two input branches, the switchover occurs when the SNR of the previously selected channel falls below the γ_T , threshold. In this case, the method is called SSC Switch and Stay Combining. Although the SSC method is less complex, it is not able to select the channel with the highest SNR in its process, and therefore the resulting SNR gain in output is below the theoretical similarity of SC signal selection. It can be shown that, for the optimally chosen threshold level a γ_T , the probability distribution of the output SNR of the SSC signal selector is the same as that of the ideal SC procedure.

The disadvantage is that in the case of a random decision, if the selector does not find a channel above the threshold level when switching branches, it will enter a continuous channel search cycle until a more favourable reception condition occurs, forcing the transmission system to switch to a reception situation below the threshold level.

Arithmetic operations and continuous estimation of the actual signal-to-noise ratio (SNR) of channels are time and energy-consuming, which is impractical for some wireless communication systems. To further reducing the complexity of implementing a diversity reception scheme, a switching and sustaining signal combining (SSC) scheme was considered. In the SSC scheme, the receiver only needs to monitor and estimate the channel state of the single branch being used. The switch-based SSC method is particularly advantageous for receiver devices (e.g. mobile devices) where processing capability is limited due to other circumstances (e.g. limited power supply).

Maximum Ratio Combining

The Maximum Ratio Combining (MRC) method takes all incoming branches into account in a weighted way, so none of the values of α_i in this method is zero. Branches with a worse individual SNR are given a lower weighting, and channels with a better SNR are given a higher weighting in the resulting output signal. (Figure 6.)

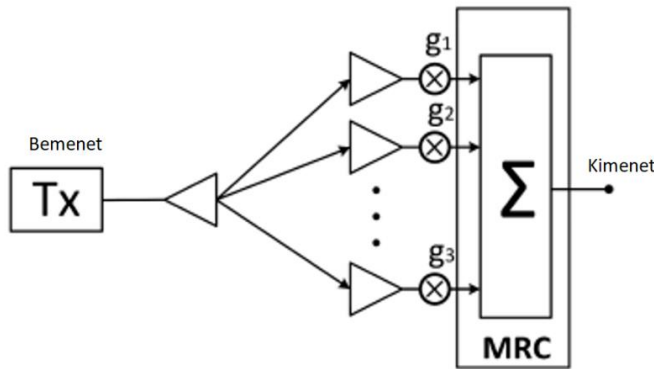


Figure 6. MRC Maximum Ratio Combining procedure block diagram
Source: [32] (Accessed: 01.10.2022)

Since the incoming branch signals are phase-matched, each branch

$$\alpha_i = a_i e^{-j\theta_i} \quad (7)$$

where θ_i is the phase of the i -th branch signal. The envelope r of the output signal of the signal combiner is

$$r = \sum_{i=1}^M a_i r_i \quad (8)$$

Assuming the same noise spectrum distribution probability on each input branch, the total instantaneous output noise power of the signal conditioner

$$N_{tot} = \sum_{i=1}^M a_i^2 N_0 \quad (9)$$

from which the output SNR is

$$\gamma_{\Sigma} = \frac{r^2}{N_{tot}} = \frac{1}{N_0} \frac{(\sum_{i=1}^M a_i r_i)^2}{\sum_{i=1}^M a_i^2} \quad (10)$$

is given by.

To produce an optimal output signal, each α_i -s must be chosen such that γ_{Σ} takes the maximum value. It can be seen that for this, branches with higher SNR values must be considered with a higher weight, while those with lower values must be considered with a lower weight, so that the weighting factors a_i^2 of the branches will be proportional to the SNR values r_i^2/N_0 of each branch. With the optimal $a_i^2 = r_i^2/N_0$ weighting, for the output noise we get:

$$\gamma_{\Sigma} = \sum_{i=1}^M r_i^2 / N_0 = \sum_{i=1}^M \gamma_i = \sum_{i=1}^M \gamma_i \quad (11)$$

It follows that for optimal weighting, the output SNR noise factor will be equal to the sum of the individual noise factors of the input branches. It can be seen that, in contrast to the SC and SCC methods, the averaged SNR noise factor of the MRC signal combiner increases in direct proportion to the number M of input branches. Similarly to the SC method, the output channel will not have a Rayleigh distribution for any number of input Rayleigh type channels. Assuming the same average $\bar{\gamma}$ SNR value of Rayleigh type on each

branch, the resulting a γ_Σ noise distribution results in a distribution of χ^2 - with $2M$ degrees of freedom

$$\bar{\gamma}_\Sigma = M\bar{\gamma} \tag{12}$$

with expected value and standard $2M\bar{\gamma}$ deviation:

$$p_{\gamma_\Sigma}(\gamma) = \frac{\gamma^{M-1} e^{-\gamma/\bar{\gamma}}}{\bar{\gamma}^M (M-1)!}, \quad \gamma \geq 0 \tag{13}$$

The corresponding γ_0 output power probability value is a function of a given threshold:

$$P_{out} = p(\gamma_\Sigma < \gamma_0) = 1 - e^{-\gamma_0/\bar{\gamma}} \sum_{k=1}^M \frac{(\gamma_0/\bar{\gamma})^{k-1}}{(k-1)!} \tag{14}$$

The correlation shows that the MRC method is significantly more effective in improving SNR than SC or SCC methods. The MRC method requires knowledge of the instantaneous SNR values for each branch, a quantity that cannot be measured continuously by simple methods (Figure 7.)

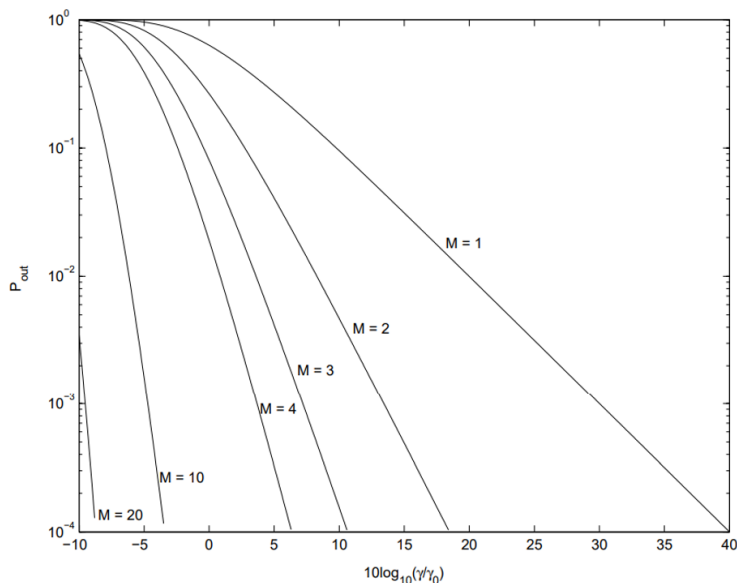


Figure 7. Outage Probability of MRC Maximum Ratio Combining in Rayleigh Fading channel
Source: [32] (Accessed: 01.10.2022.)

From the mathematical model of the MRC procedure, it can be deduced that the resulting SNR gain of the signal combiner will be equal to the sum of the SNR gains of the individual channels. The average SNR gain of the combiner increases with the number of diversity branches in direct proportion to the number of diversity branches, unlike in the SC procedure. Note, however, that even though the fading distribution of the individual branches is Rayleigh, the output will no longer have this property (χ^2 - distribution). Increasing the number of receive branches in this procedure will yield a more significant SNR gain compared to the SC and EGC procedures, but its implementation may be difficult in some cases, as continuous measurement of time-dependent individual SNR values on all channels may be difficult.

Equal Gain Combining

Equal Gain Combining (EGC) is a simpler solution that makes the incoming individual channel signals coherent and combines them with the same $\alpha_i = e^{-j\theta_i}$ weighting. (Figure 8.)

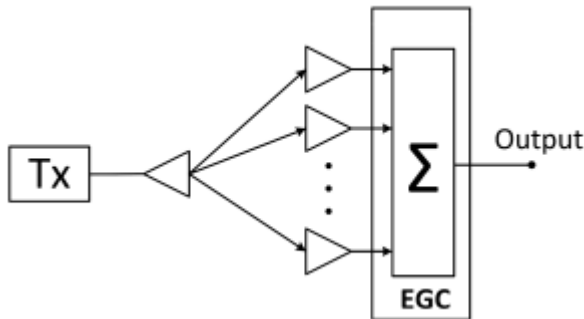


Figure 8. EGC Equal Gain Combining procedure block diagram
Source: [32] (Accessed: 01.10.2022.)

Assuming the same magnitude of the eigennoise power spectral distribution probabilities on each branch, the resulting output SNR value will be better than the SNR value of any individual channel.

$$\gamma_{\Sigma} = \frac{1}{N_0 M} \left(\sum_{i=1}^M r_i \right)^2 \quad (15)$$

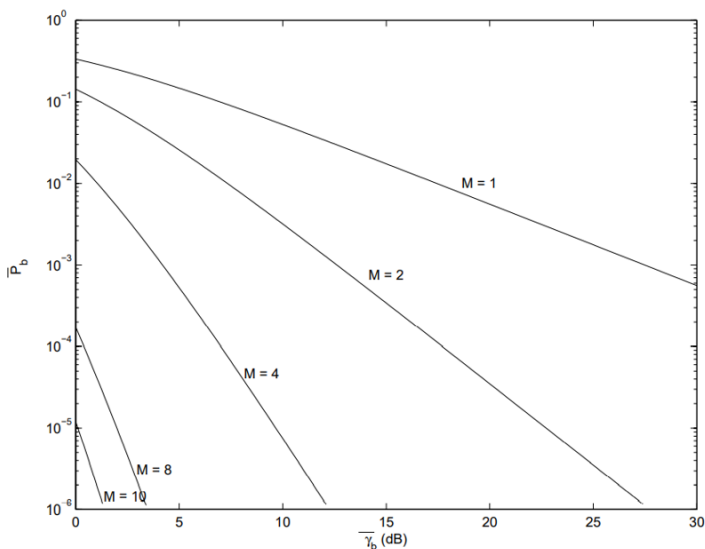


Figure 7. Outage Probability of EGC Equal Gain Combining in Rayleigh Fading channel
Source: [32] (Accessed: 01.10.2022.)

Its implementation requires complicated circuit considerations, but it can be used with good efficiency in cases where it is not possible, or only to a limited extent, to determine the characteristics of individual channels.

In my research, the real measurement data of diversity receivers are presented at the level of demodulated and decoded communications. From a signal combining point of view, the off-line combining method I use (baseband and simultaneous receiver diversity) is approximately equivalent to the SC Selection Combining method among the above signal combining methods, and therefore I interpret my investigations in this category.

SUMMARY THOUGHTS, CONCLUSIONS

The theoretical effectiveness of diversity assumptions is essentially based on a theoretical study of the signal combining procedures that can be applied. Among the conventional signal-combining techniques, SC, EGC and MRC are the most relevant for spatial diversity.

My simulation studies presented for the investigation of signal-combining techniques have demonstrated that the variation of SNR gain as a function of the channel number of the diversity shows clear positivity. At the same time, the simulations have also shown that the largest incremental gain in this respect is obtained by integrating the first tributary branch into the system. With further increases in the number of branches having smaller and smaller returns in specific terms. For this reason, the possibilities for increasing the gains in the case of spatial diversity are significantly limited from both theoretical and a resource point of view.

The bit-rate and bit-time SNR for different channel models show similar trends, but when comparing AWGN and Rayleigh channels, AWGN shows more favourable values.

Increasing the distance of the diversity receiving antennas is decisive for the diversity gain up to a distance of $\lambda/8$, above which the gain increment decreases significantly.

The relative gain sensitivity of the combination modes to each other as a function of SNR change can be easily and visually demonstrated using this method, whereas it could not be demonstrated using the same parameter-based comparisons used in conventional previous work.

The improved simulation procedure system developed and developed for the investigation of spatial-diversity-based combinatorial methods presented in this paper provides a more detailed evaluation capability for diversity studies than previously available.

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