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Massive diversity for 5G and beyond

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Abstract

Radio communications have now widely penetrated both the professional and private spheres, for everyday uses of largely differing importance and criticality that are anticipated to further increase in the coming years through 5G networks and the internet of things. This will address major "vertical" applications such as smart homes and smart cities, agriculture, connected and autonomous vehicles, health, industry and many others. While in some cases the failure of the radio link is tolerable and without serious implications, in others reliability will be critical and unavoidable. Unfortunately, the laws of electromagnetics are such that numerous effects are detrimental to the link budget, are varying and are uneasily controllable. In this context, how to ensure a very high level reliability, which solutions are feasible and up to which degree of complexity? This paper recalls the physical and technical sources of an uncertain reliability for the radio link, in relation with antennas and propagation, and evokes "massive diversity" as a future development to guarantee a constant connectivity service with ultra-high reliability.

1. Introduction

Achieving 100 % reliability for a radio link is just impossible. However approaching this number e.g. up to 99.9999 % may be a target for extremely demanding (critical) services. Such a high level of reliability can only be reached by tracking all sources of unreliability in the system (including and special software), but here we only address the radio link part, in connection with antenna and radio propagation aspects. Since there is no cable between the transmitter (Tx) and the receiver (Rx), the propagation medium suffers many impairments from the point of view of the communication, and is commonly seen as moderately safe and moderately reliable. Given the important and increasing impact of wireless communications today, this paper addresses ways to enhance the wireless link reliability in the context of 5G and beyond 5G systems.

2. Mitigating radio link unreliability

2.1 physical causes of radio link unreliability

- Often enough the source and the destination are not in line of sight (LOS), with scattering/absorbing obstructions in between, resulting in a propagation exponent well greater than 2
- Antennas often deviate much from isotropy, whether it was intentional or not
- Interferences may occur, which handicap the capability of a receiver to discriminate between sources

2.2 Basics of diversity techniques

The problem can be seen through a risk analysis, given that the radio link failure can be expressed as the probability that a certain parameter (e.g. a received power signal, or a signal/interference+noise ratio, or a bit error rate) be below a certain threshold. A well-known mitigation approach is to combine differing signals, with independence or at least decorrelation between them, so that a suitable combination results in a much lower threshold than for the individual signals. Diversity techniques have been used already in the twenties to that aim, and have since that time exploited in numerous communication schemes for enhancing the link robustness.
In this paper, we draw a list of the relevant diversity techniques useable in the context of upcoming and future wireless networking of devices, with a highlight on the socio-economic aspects. These techniques imply that the same data is transmitted on differing communications channels, the most common being [1]:

- Frequency diversity (FD), implying differing frequency channels or in differing bands (BD)
- Polarization diversity (PD) using two orthogonal polarizations, e.g. linear or circular
- Antenna diversity (AD), where e.g. the radiation patterns cover differing angular sectors
- Spatial diversity (SD), making use of at least two antennas placed at differing positions, often in close proximity (with at most a few wavelengths) but sometimes widely separated (macro diversity: MD)
- Time diversity (TD), where the signals are transmitted at differing time instants

These techniques are all based on the assumption that the signals are attenuated or interfered differently in the differing communications channels, which can be physically justified by the following phenomena:

Multipath propagation, which may result in destructive interference of additively combined signal replica at a given frequency, or for a given antenna position, hence FD and SD benefits. PD and AD stem from the filtering role of the antenna, which multiplies (in reception) the multipath complex amplitude by a complex antenna gain coefficient that differs with the antenna polarization or the antenna directional pattern. TD comes from the fact that the radio channel is not usually perfectly constant in time, mostly due to the transmitter (Tx) or receiver (Rx) movements, and to some extent to subtle temporal variations of the propagation environment (which is never free space).
MD as well as AD have a particular relevance to mitigate major obstructions between Tx and Rx, as these techniques exploit the strong impact of the multipath structure and associated multipath gains for widely differing Tx-Rx positions or for antennas steered in differing directions.
Apart from the choice of the diversity technique(s) used in a given use case, the method for combining signals has a significant impact on the performance. Simplistic ways such as picking the best received signal is a possibility, but linear combining according to the “maximum ratio combining” or to more sophisticated optimization criteria significantly improve the performance, especially for more than two signals. Relaying, or a more modern approach such as network combining can also be seen as a way to combine signals between Tx and Rx through differing propagation channels involving an intermediate device.

2.3 Statistical aspects

2.3.1 Rayleigh distribution

The performance of diversity techniques is heavily dependent on the probabilistic nature of the incoming signals at the Rx antenna output. For e.g. SD or TD techniques, it is commonplace to consider these signals to be identically distributed Rayleigh, or Gaussian when considering the real/imaginary components of the I-Q baseband signal. In such a case the probability distribution of the received signal goes from the very poor Rayleigh to a much steeper one, with an effective gain given depending on the number of (independent) diversity branches and acceptable link failure probability. For correlated branches, the gain is reduced.
Such techniques can, hence, provide effective gains of tens of dB, provided there are enough little correlated diversity branches. This encourages a large number of device antennas, although the mean SNR gain tends to saturate as M increases.

2.3.2 Lognormal distribution

The deviation from identically distributed Gaussian/Rayleigh probabilities will very much impact the performance of diversity schemes as recalled in the previous section. For instance, in the case where one branch has a smaller mean power than the others, it will not be effectively useable since it can less efficiently counteract the destructive interference experienced by the other signals. This can arise when one antenna is permanently or temporarily masked by an obstruction.
The well-known lognormal distribution is assumed to describe well an obstructed environment, due to the multiplicative nature of successive attenuation events, independent and identically distributed, resulting in a Gaussian distribution of the path loss expressed in dB.

2.2.2 Other distributions

The relative regularity of Rayleigh and lognormal distributions is not always respected, observed ones sometimes present thick “tails”, which are highly detrimental to a radio link quality when extending deeply into the negative region of the path gain. This happens, e.g., when obstructions behave as discrete and major attenuators rather than numerous and adding to each other (fig. 1).

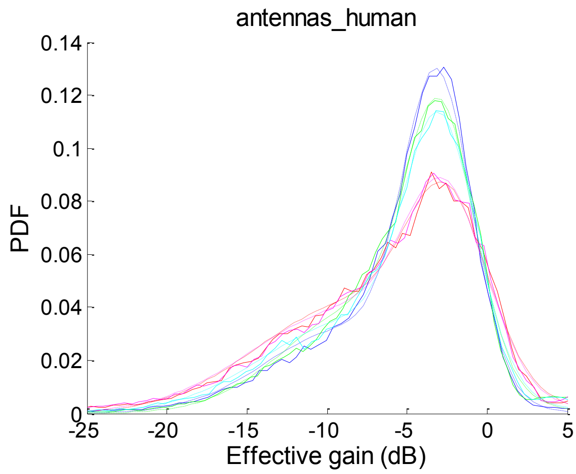

Figure 1. Statistical distribution of the effective gain of a laptop antenna, showing a thick tail due to body obstruction (from [2])

3. Massive diversity

3.1 Benefits and capabilities

The goal of ultra-high link reliability targeted in the introduction can be achieved by a “massive diversity” approach, where a large number of wireless nodes can very efficiently mitigate the impairments mentioned in 2.1 owing to the techniques recalled in 2.2. The simple idea is to surround any connected device (fixed or mobile) by an ocean of EM waves, operating at different frequencies, originating from differing directions, and at relatively short distances, so that the communications was very stable whatever the instantaneous and local status.
However, as mentioned in section 2.3.1, the benefit of such a massification saturates at a large number of antennas when the signals are identically and independently distributed. This is less true when the

nature of the statistical distributions differs (e.g. lognormal vs. Rayleigh), in relation with the physical origin of these distributions. For instance:

- FD as implemented within a given frequency channel (e.g. 20, 40, 80 or even 160 MHz band width for 802.11ac WIFI) already mitigates “fast” fading due to multipath interference, through an adequate correction coding scheme
- BD can also mitigate fading occurring over a whole frequency channel (e.g. when the coherence band width of the channel approaches or exceeds the communication band width but is smaller than the gap between bands). This is typically efficient for a transmission operated simultaneously on the 2.4 and 5 GHz WIFI bands

Another indirect benefit of BD is the fact that antenna radiation patterns may very much differ from one frequency band to another, while they are generally constant over a narrow or moderate band width. This means that, if a major propagation path falls into a pattern null for one frequency band, this will likely not be the case for another band. In the hypothetical example of fig. 2, the antenna gain is weak and irregular in the horizontal azimuth plane for two frequency bands, while it is much higher for a third band. The physical reason is that the interfering electromagnetic phenomena within an antenna may favor radiation at elevated angles for certain frequencies, and at low angles for others. This problem may arise even for well-designed antennas, because of the near field interactions between the antenna and its immediate environment (such as supporting structure, close-by wall… see e.g. [3]).

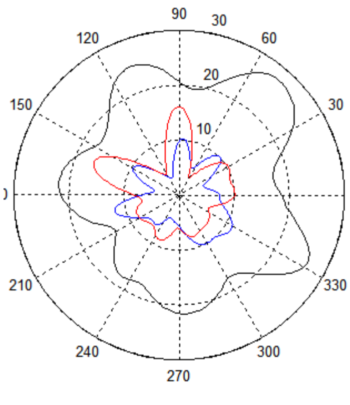

Figure 2. radiation patterns in the azimuthal plan in 3 different frequency bands (in relative dB units) (from [4])

AD may be operated in several ways. An old one is to equip a device with several directional antennas, covering a set of angular sectors. Then, a suitable selection or combination scheme of the output signals allows to recover enough dynamic range from one unfavorable to another better pointing toward strong propagation paths. Statistically, the gain is proportional to the number of antennas (or sectors). However, in a given case it may be much better, depending on the “matching” between the antenna patterns and the local multipath structure. Still, this solution is completely static and is unable to adapt to the local context. More advanced schemes make use of systems of multiple omnidirectional radiators, for which the equivalent pattern synthesis can be achieved through signal processing. Such adaptive antennas furthermore very much simplify the design of the antenna system, at the expense of processing power (and energy consumption) in the receiver. SD is a special case of multiple antenna processing.
Actually, a very powerful way to enable a communication link for a highly faded propagation path is through MD. The reason is simple: even in LOS, $(2d)^2$ is larger than d^2, in other words placing an “amplify and forward” relay at mid-distance between two nodes effectively reduces the attenuation distance by a factor two. In a deeply faded link, the benefit can be enormous, allowing to gains tens of dBs over the attenuation (e.g. the notion of “gap fillers”).
In other words, implementing all the diversity techniques above can result in a very large effective gain vs. the simple case of a narrowband single antenna isolated device. The foreseen problems are the following:

- Cost of each device
- Energy consumption (in particular accounting for heavy local signal processing)
- Necessity of redundancy in the placement of devices
- Optimization of the networking

The latter feature can just be ignored (e.g. through random or simply intuitive placement of the devices), or it can be duly implemented, owing to sophisticated self-optimizations tools able to grasp the local structure of the exchanged signals and to react on their configuration. Alternatively, site specific deployment tools (such as done for the cellular networks with planning tools) can be used in order to find the best location for nodes.

3.2 System and scenarios

According to the previous considerations, a system approach for 5G and beyond 5G wireless connectivity ensuring a quasi-constant service to users with ultra-high reliability might be the following: a dense distribution of wireless nodes, with several sorts of nodes, ranging from

- high performance nodes (in small number), ensuring the internet/cloud connectivity and smart multiband beamforming (including massive MIMO antennas), at low density locations
- intermediate performance node, with one/few antennas but significant processing capabilities and distributed at strategic places
- low-cost/ultra-low power nodes, enabled with multiband operation with specially designed antennas to ensure quasi random radiation patterns in all directions with high frequency dependence of the

patterns. Such nodes should be massively distributed, including with high redundancy

The distribution of either kind of device will obviously be scenario dependent. However a major difficulty is that of the energy source for massively distributed nodes. The answer to this vast problem is well beyond the scope of this paper. However, some remarks can be made:

- massively distributed devices should be low-power, owing to the small distance with the connecting devices and the power sharing between devices
- this can facilitate wireline empowering, reduce the capacity of a local battery or make more feasible energy harvesting

Further consideration can be found in a smart deployment of massively distributed nodes. While an initial deployment might be more or less random or intuitive, automatic learning according to the true operation of the wireless access network may help improve its performance, through measuring the level of activity of nodes, and an update of the deployment. Based on the idea that massively distributed nodes are very low cost and extremely easy to settle will make an update of the nodes deployment similarly easy.

4. Conclusion

This paper is an advocacy of the benefit in massively exploiting diversity techniques in the design and deployment of communicating devices, in order to provide high reliability radio links for 5G and beyond 5G networks.

5. References

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