Channel Characterization Using Radar for Transmission of Communication Signals

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***Abstract*—**

As radar and communication systems both are RF systems, a combination of both may be possible. The communication channel between transmitter and receiver is modeled and then adapted to include a rotating narrowbeam antenna, common to radar systems, located at the transmitter side. Assuming an omnidirectional antenna at the receiving station, this channel model can help to understand the similarities, differences and possibilities of the combination of radar and communication. Then the channel capacity is analyzed using this system setup. Whether this channel capacity can be approached or not depends on the channel realization and the possible presence of Doppler. Further, this paper will discuss the effects of Doppler and a possible solution to deal with the resulting reduction in performance. Finally, the effective beamwidth of the narrow beampattern is determined, using the channel model and assuming the receiver deals with the channel (and Doppler shifts) perfectly.

I. INTRODUCTION

Often, ground-based surveillance radars operate monostatically. These radars do not need to communicate with other radar stations. If communication must be implemented, several methods, for example a GSM system or other wireless communication means, might be used. The environment of the radars may however not guarantee the successful implementation of these systems. Furthermore, communication integrity may be harmed due to signal interception by non-friendly parties. Therefore a possible solution is to embed the communication signal in the powerful radar beam.

When considering the scenario of a network of surveillance radar stations, there is a need to communicate. These stations can detect the same objects looking from different aspect angles. The strategy is to enhance the detection of very small targets by sharing information through a communication signal embedded in radar. In this paper, only two stations of this radar network are considered. The transmitting station is assumed to use a typcial radar antenna; a rotating antenna with a very narrow beampattern. The receiver is a radar station too, but only the communications receiver with an omnidirectional antenna, collocated at the receiving radar station, is considered. Although the analysis is mainly on the communication link, outputs from radar operation may be used to improve the processing and results at the output of the communications receiver.

The communication link is represented by a multipath channel model. As a rotating very narrow beam is not common to communications, a channel model must be developed that includes this. The channel model represents propagation and reflections from the environment. Due to the transmitter antenna directivity, the statistics of these reflections change as a result of the rotation. Several parameters affect the link quality and thus the channel capacity.

In section II, the channel model is introduced and shows how the rotating variable gain transmitter antenna can be included. Representative channel realizations are discussed for both the mainlobe Line-Of-Sight (LOS) connection and the Non Line-of-Sight (NLOS) scenario with the mainlobe *not* pointing in the direction of the receiver. Section III discusses OFDM system parameters and the differences and similarities between radar systems and communication systems. Section IV shows the results for the channel capacity to give an indication of the effects of the very narrow beampattern including the effective beamwidth. Finally, section V concludes the discussions.

II. CHANNEL MODELING

A. General

The wireless channel represents the reflections, signal copies, from the environment arriving at the receiver. Assuming BW is the system bandwidth, the receiver samples with intervals of $t_{spl} = 1/BW$. As the receiver cannot resolve paths within a sampling interval, they can be combined constructively or destructively, resulting in a fading channel. The received signal is represented by [1]:

$$r(t) = \int_{-\infty}^{+\infty} h(t,\tau)s(t-\tau)d\tau + n(t) \qquad (1)$$

with τ representing a delay, $n(t)$ the noise, $s(t)$ is the transmitted signal and $h(t,\tau)$ represents the, possibly time-variant, channel [2] with L taps (arriving echoes) modeled as [1]:

$$h(t,\tau) = \sum_{l=0}^{L} \alpha_l(t)e^{j2\pi f_c \tau_l(t)}e^{j2\pi f_{D_l} t}\delta(t-\tau_l(t)) \qquad (2)$$

The complex amplitudes of the echoes are represented by α_l, which include an unknown phase shift caused by the objects' shapes, sizes and orientations w.r.t. the receiver. An impulse is represented by $\delta(t)$, the carrier frequency by f_c, delays τ_l introduce additional phase shifts and moving objects may cause the channel to be time-varying resulting in a Doppler frequency f_D:

$$f_D = \frac{v}{\lambda} \cdot (\cos\theta_1 + \cos\theta_2) \tag{3}$$

Here, λ is the wavelength, θ_1 and θ_2 are the angles of a moving object with respect to the transmitter and receiver, respectively. Equation (3) shows that the resulting Doppler frequency, seen by the receiver, depends on the combination of both angles θ_1 and θ_2. The Doppler effect results in a phase shift changing with time. Since it is hard to model all amplitudes, delays and phases deterministically while maintaining a generally applicable model, these parameters will be modeled stochastically.
The bulk delay is represented by the time it takes for the signal to travel from transmitter to receiver over the baseline (LOS link). Hence, it is assumed that the LOS link exists at all time (no obstruction on the baseline). For sake of simplicity, the bulk delay (corresponding to the LOS link delay) is assumed $\tau_0 = 0$ without loss of generality.

An exponentially decaying statistical model for typically urban environments [3], [4], [5], [6] is used to model the channel, also known as the COST207 model. The arrivals are determined stochastically using the Poisson distribution [3] and the path gain of the l^{th} path is described by a probability density function (pdf) with a Rayleigh distribution [3]. The *mean* path power gain for path l is determined by:

$$\overline{\alpha}_l^2 = \overline{\alpha}_0^2 \cdot e^{-\tau_l \cdot \gamma} \tag{4}$$

with γ an exponential decay factor. The mean path power gain of the first arrival (assumed to be the LOS arrival) is [4]:

$$\overline{\alpha}_0^2 = G_T G_R \cdot \left(\frac{\lambda}{4\pi}\right)^2 \cdot \frac{1}{d_{ant}^2} \cdot \frac{1}{\lambda_h} \tag{5}$$

which can be found using Friis equation for free space loss [2], normalized with respect to the mean echo arrival rate λ_h. G_T is the variable transmit antenna gain (depending on the beampattern), G_R the receiver antenna gain and d_{ant} is the distance between transmitter and receiver.

B. Channel with rotating antenna

When assuming a multipath environment and a directive variable gain rotating antenna, the channel can be modeled by two components. To develop a full model, the exponential decaying model is used, but modified to include the effects of the rotating antenna.

It can be understood that the channel statistics with a mainlobe LOS connection are different from those with the mainlobe pointing in another, arbitrary, direction. In the first case, the connection can be considered very strong in which most of the echoes can be ignored because their amplitudes ($\alpha_1 \ldots \alpha_L$) are likely to be much weaker than that of the first arrival (α_0), which is assumed the LOS link.

In order to tune the exponentially decaying channel model, two parameters are used to adjust the channel statistics: the Ricean K-factor and the rms delay spread, τ_{rms} [5], [6]. They can be used to set up a model that describes the change of channel statistics due to the rotation of the transmitter antenna. The K-factor describes the power of the LOS path compared to the sum of the power of all echoes. In case the LOS link is dominant with respect to the echoes, the communications link is considered strong. This means that the mainlobe should be (approximately) directed towards the receiver station, called mainlobe LOS connection. RMS delay spread describes that part of the channel delay profile that contains most power. A varying τ_{rms} can be understood with help of the very narrow beampattern.

An ideal channel can be represented by free space loss only, a nearly ideal channel also includes very weak multipath components (compared to the LOS arrival). This results in a short and powerful channel, with τ_{rms} very small, and K very large, see also [8]. When the rotating transmitter antenna moves away from the receiver, the K-factor will drop rapidly to low (near zero) values because the powerful beam will illuminate other objects (if present). The LOS connection might exist through the possible presence of sidelobes of the beampattern, *if* they are powerful enough to provide a link suitable for communications. Values for τ_{rms} will increase gradually representing more (or even most) energy, located further away from the LOS arrival. The K-factor, τ_{rms} and the exponential decay factor are interrelated [7]:

$$\gamma = \frac{1}{\tau_{rms}} \frac{\sqrt{2K+1}}{K+1} \tag{6}$$

This result is used in equation (4) to complete the relation between the channel taps. It can be understood that an increase of τ_{rms} results in a small decay factor γ, which in turn results in larger values of $\overline{\alpha}_l^2$. Since the receiver threshold is assumed constant, more delayed signal copies are detected at larger delays, making the channel longer.

It can be concluded that the channel representation changes from a, nearly ideal, strong Ricean channel ($K \gg 0$, see also [8]) with small τ_{rms} to a Rayleigh channel ($K = 0$) with larger τ_{rms}.

With the channel model in place, the channel capacity becomes an important feature of the system to investigate the use of the very narrow beampattern for communications. The channel capacity serves as a starting point since it is a theoretical limit for any practical implementation. Up to what extent this capacity can be approached depends also on impairments such as Doppler, discussed in next section.

III. COMBINING RADAR AND COMMUNICATIONS

A. OFDM

For the network of radars OFDM was selected. An Orthogonal Frequency Division Multiplexing (OFDM) system [1] divides the total system bandwidth into smaller frequency bins. N_{SC} subcarriers are equi-spaced by $\Delta f \approx BW/N_{SC}$. All subcarriers are orthogonal with respect to each other and transmission of a single OFDM symbol takes an interval, $t_s = 1/\Delta f$, called OFDM symbol time. In order to overcome Intersymbol Interference (ISI) due to the channel, a guard interval of at least the same length as the channel must be implemented. In this paper, the radar is a simultaneous Multiple Frequency Continuous Wave (MFCW) radar [9] which implements the OFDM modulation scheme.

In order to satisfy radar requirements for large range measurements, a large number of subcarriers (N_{SC}) is implemented. A large N_{SC} is justified when realizing that in MFCW radar, range measurement depends on the spacing between the subcarriers. The maximum unambiguous range for radar is expressed as $R_{unamb,max} = c/(2\Delta f)$. Although N_{SC} is allowed to be smaller, N_{SC} = 300000 will be used as a benchmark in order to investigate its effects on the OFDM communications system. Note that this is too large for a communication system, but for radar it turns out to be beneficial. Other solutions must be implemented to provide a workable communications system without affecting N_{SC} = 300000. For example, grouping by transmitting the same symbol on consecutive subcarriers.

B. Time-varying channels

When, in addition to the fading characteristics as discussed in section II, the channel is also time-varying due to moving objects, the communication receiver also has to deal with this situation. For radar operation, Doppler measurement is a basic functionality, but for communications, this may pose problems. In case of a time-varying channel, the subcarriers are shifted with respect to each other, which results in loss of orthogonality. The resulting Intercarrier Interference (ICI) can be large because Δf is small (1kHz, for N_{SC} = 300000), causing the system to be very sensitive to small Doppler shifts. As a result, the frequency domain channel matrix in OFDM loses its property of being diagonal [10]. Instead, it becomes (approximately) banded.

Due to the large number of subcarriers required for radar operation, common channel estimation algorithms are a significant computational burden for the receiver. This is due to the calculation of all $L+1$ channel coefficients for all N_{SC} samples (assuming ciritical sampling).

Instead of calculating the total of $N_{SC}(L+1)$ coefficients, much less coefficients need to be calculated when Basis Expansion Models (BEMs) [10] are used. BEMs exploit the previously discussed bandedness of the frequency domain channel matrix. In a BEM, each path is written as a linear combination of fixed basis functions. The coefficients can be considered stochastic or deterministic.

An example of a BEM is the Complex Exponential-BEM (CE-BEM) which uses a Fourier basis to model the channel. For the CE-BEM, the number of basis functions $Q+1$ is determined by [11]:

$$\frac{Q}{2\kappa t_s} \geq f_{D,max} \tag{7}$$

Here, κ is the oversampling factor and $f_{D,max}$ is the maximum Doppler frequency in the channel. Since there are $L+1$ taps in total, $(Q+1)(L+1)$ taps are to be estimated, which is much less than $N_{SC}(L+1)$ because $Q \ll N_{SC}$. The modeling error depends on the Basis functions (BEM model) chosen and the actual channel, κ and the interference not taken into account. When $\kappa = 1$, the error is substantial. A larger κ result in smaller modeling errors. The modeled frequency domain channel matrix bandedness is determined by Q/κ. Values for κ and Q determine the amount of ICI that is allowed in the system and can be chosen arbitrarily as long as their relation with the maximum Doppler shift, as given in equation (7), holds. Reference [10] shows more details about the use of Basis Expansion Models.

Equation (7) provides a means to combine radar and communications. Radars can easily measure Doppler and pass this information to the communications receiver. Instead of designing Q in advance and taking into account a worst case scenario, the number of basis functions Q can be adjusted to the maximum Doppler in the channel, assuming that the information is valid for several consecutive OFDM symbols.

IV. SIMULATION

A. Channel capacity

In this section the channel capacity is determined including the radar antenna. The channel capacity for the wideband system can be found using the equation for Shannon's capacity [2], by calculating the capacity for each frequency band (bin) of the OFDM system and taking into account the channel frequency response:

$$C = (\delta) \cdot \int_{-\infty}^{+\infty} \log_2 \left(1 + \frac{|H(f)|^2}{P_N}\right) df \tag{8}$$

Using Δf, equation (8) can be rewritten as the summation over all frequency bins. The received power is represented by $\alpha^2 \cdot |H(f)|^2$ with $\alpha^2 = \overline{\alpha}_0^2$, using the Friis equation [2] or equation (5) with $\lambda_h = 1$. Noise power is calculated by $P_N = \sigma_n^2 = kT_0FBW$ with F the receiver noise figure, k is Boltzmann's constant and T_0 is the standard temperature. Finally, δ represents a radar specific operation parameter: the duty cycle, which is an indication of the time the transmitter is transmitting, relative to the time it could have been transmitting. In figure 1, the pdf of the channel capacity is shown. To calculate the probability of capacity p_{C_p}, the throughput is split in discrete bins p. Summing and comparing the occurrences in bin p, using equation (8), the expected value of capacity can be calculated:

$$p_{C_p} = \frac{\sum \text{occurrences of } C_p}{\sum \text{occurrences of } C_{p'}} \qquad (p' = 1 \ldots P, p' \neq p) \tag{9}$$

$$E[C] = \sum_{p=1}^{P} p_{C_p} \cdot C_p \approx 5.24\text{Mbit/s} \tag{10}$$

As equation (10) shows, capacity C for the entire bandwidth is obtained by the summation of all C_p. Since this figure only shows the maximum throughput possible for a single channel,

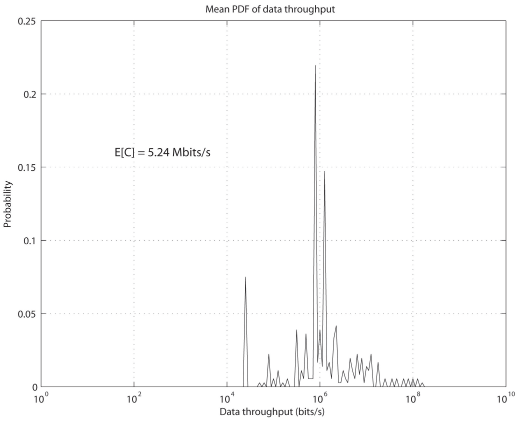

Fig. 1. PDF of channel capacity using $N_{SC} = 1024$, based on G_T in the direction of the receiver.

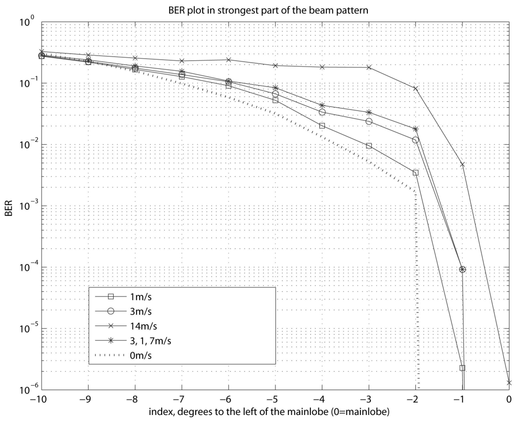

Fig. 2. BER results for the time-varying channel simulating the rotating radar antenna.

the actual throughput depends on the receiver implementation and the possible cooperation between radar and communications to approach the capacity as given in figure 1.

B. *Effective beamwidth for communications*

It is important to know when the communications channel can be used for transmission of data symbols. This strongly depends on the environment, the narrow beampattern and its beamwidth. The effective beamwidth is defined as that portion of the total beampattern that can be used for transmission. A realistic radar antenna pattern was used; the -3dB beamwidth of the pattern is equal to $1\,^{\circ}$. Using the channel model for a rotating antenna and the narrow pattern as described in section II, the effective beamwidth can be determined using the Bit-Error Rate (BER). When BER is large, the communication link is considered unreliable. Assuming no error-correcting coding is implemented, the maximum BER limit is arbitrarily set to 10^{-4}.

Figure 2 shows the simulation results for the channel model of section II with several (maximum) velocities. The introduced Dopplers cause the BER to get worse. From figure 2 it can be concluded that for relatively low velocities, the effective beamwidth is quite narrow (as expected). However, since the channel capacity in this small section of the beampattern is very large, the simulated expected value for the capacity is approximately $E[C] \approx 122$ Mbits/s, simulating over an effective beamwidth of $5\,^{\circ}$ in total, again using $\delta = 0.1$.

V. CONCLUSION

In this paper, the channel model was shown to vary statistically, depending on the pointing of the very narrow beam transmitter w.r.t. the receiver. To this end, the exponential decaying model provides two tuning parameters: K-factor and τ_{rms}. These are used to simulate the rotating transmitter antenna. During simulation, this channel model can be used to obtain the effective beamwidth, which turns out to be slightly larger ($3\,^{\circ}$) than the -3dB beamwidth of the beampattern ($1\,^{\circ}$). It strongly depends on the environment and receiver implementation. The effective beamwidth can be used to investigate the mean capacity in this section of the beampattern.

As the communication system is embedded in a radar, it has to deal with parameters set for radar operation. One of these parameters is a large N_{SC}, which causes the channel to be time-varying even with small Doppler shifts. Several solutions are possible to solve this problem. The OFDM system for communications can group several subcarriers by transmitting similar symbols per group, or several smaller OFDM systems can be used. Problems caused by ICI can be dealt with, using Basis Expansion Models to reduce computational load. Parameters for this modeling may be set using information from radar operation. At the receiver, channel estimation can also be enhanced using information from radar operation, not only by using Doppler information, but also by using channel information from e.g. the channel clutter map. This topic is however still open for future research.

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