

The $\kappa - \mu$ Distribution Applied to the Analysis of Fading in Body to Body Communication Channels for Fire and Rescue Personnel

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Abstract—In this letter, we perform a novel characterization of the fading experienced in body to body communications channels for fire and rescue personnel using the recently proposed $\kappa - \mu$ distribution. A transmitter positioned on the lead fire person and four strategically placed, time-synchronized 2.45-GHz receivers situated on the protective helmet and shoulders of another team member allowed small-scale signal variation to be recorded while a rescue team of four persons performed a building sweep and search type operation. A general $\kappa - \mu$ model with parameters $\kappa = 2.31$ and $\mu = 1.19$ was obtained using maximum likelihood estimation and shown to provide a good fit to measured data. Level crossing rates for these channels are also presented.

Index Terms—Bodyworn antennas, bodyworn channel, $\kappa - \mu$ distribution, wireless personal area networks.

I. INTRODUCTION

IN 2005, fire was responsible for the deaths of 3565 civilians in the United States [1] and 491 in the United Kingdom [2]. The majority of fires occur in domestic premises where space may be confined and radio channel conditions are often at their most dispersive. The physical maneuvers required to search for casualties further compounds the communications problem, adding to the antenna-body interaction effects [3] and complex propagation mechanisms associated with bodyworn systems [4]. Another issue which may be prevalent when performing sweep and search type operations is the intermittent attenuation of the received signal. This may occur when individual rescuers are alternating between line of sight (LOS) and non-LOS (NLOS) states relative to one another due to obstruction by environmental objects, partitions and even human body shadowing [5]. Because of this, and the safety and reliability requirements for these types of applications, it is imperative that propagation conditions are investigated as fully as possible to ensure that channel impairments are well understood. Then suitable mitigation measures can be put in place, e.g., careful choice of bodyworn antenna positions.

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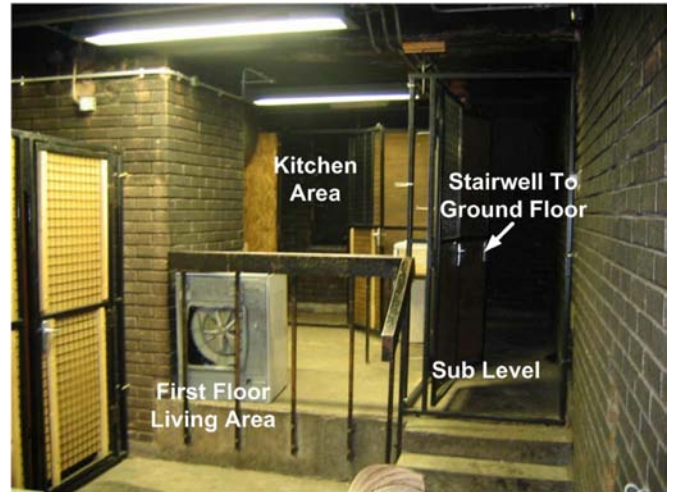


Fig. 1. First floor of test environment. Area shown contains part of the first floor living area (foreground) and kitchen area (background).

When considering the underlying factors which affect bodyworn communications and the almost limitless permutations of application and scenario, it is unsurprising that a statistical description of these channels is often favored [4], [6] over more complicated deterministic models. In this letter we consider the recently proposed $\kappa - \mu$ distribution [7]. This general fading model may be used to describe the small-scale variation of a fading signal under LOS conditions. It shows much promise in field of wireless channel characterization because, unlike the classical Rayleigh and Rice distributions, it does not assume the often unrealistic existence (indoor channels) of a homogeneous scattering environment and furthermore, through the flexibility of the tail of the cumulative distribution function (cdf) which may be adjusted to best describe practical data. The $\kappa - \mu$ distribution will be discussed further in Section III.

II. EXPERIMENTAL PROCEDURE

Measurement trials were performed over a two day period at the training headquarters of the Northern Ireland Fire and Rescue Service in Belfast, U.K. A team of four highly trained rescue personnel performed sweep and search type operations in a smoke-filled full-scale model of a two storey building constructed from metal reinforced concrete, clay based bricks and containing a number of metallic and nonmetallic obstacles. Fig. 1 shows a photograph of part of the layout of the first floor of the building, typical of the entire test environment. In this study, one of the fire personnel, an adult male of mass 98.6 kg

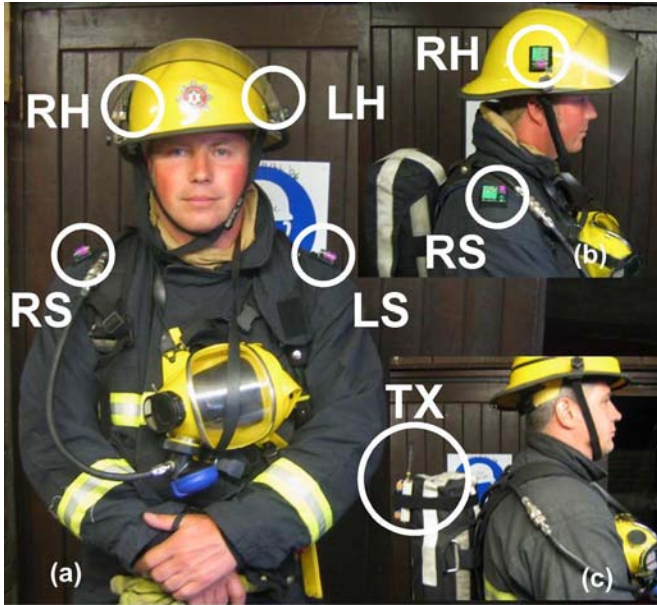


Fig. 2. Bodyworn measurement setup showing four receiver locations: right-head (RH), left-head (LH), right-shoulder (RS), left-shoulder (LS) all referenced from the test person's perspective and transmitter (TX) placed on the lead fire person's compressed air cylinder.

and height 1.88 m, was fitted with four proprietary time-synchronized, body-mounted, ultralow profile 2.45-GHz receivers placed strategically at positions on the user's right-head, left-head, right-shoulder, and left-shoulder [Fig. 2(a) and (b)]. These high body locations were chosen as these elevations are expected to suffer less from potential shadowing from obstacles in the local environment and from other pedestrians. The transmitter (TX) was fitted to the lead fire person (an adult male of mass 111.4 kg and height 1.91 m). It consisted of a NovaSource G6 synthesized RF signal source, whose output was amplified using a Hittite HMC-455LP3 heterojunction bipolar transistor amplifier to ensure adequate dynamic range at each receiver regardless of position, and a 2.0-dBi sleeve dipole antenna. The TX was mounted vertically on the compressed air tank of the test person's breathing apparatus [Fig. 2(c)] to provide as close as is practically possible omnidirectionality and configured to operate in continuous wave (CW) mode with an overall transmit power of +22 dBm at 2.45 GHz. The remaining two personnel acted as mobile scatterers.

The self-contained 2.45-GHz data logging modules were based around a Linear Technology LT5504 RF measuring receiver and a Crossbow Mica2Dot for data storage. A block diagram of the system, along with key component characteristics and dimensions is shown in Fig. 3. The 2.45-GHz receiver board included an integrated printed-F antenna, Johanson 2450BP18C100A narrowband filter, Hittite HMC-286 low-noise amplifier and the buffered local oscillator signal produced by a regulated VCO (ZComm USSP 2400), with trace widths calculated to provide a 50- Ω match between components using a ceramic loaded substrate (Taconic CER-10, $\epsilon_r = 10$). The receivers were positioned so that the radiating element of the antenna was pointing in a direction parallel to the user's body. The printed-F antenna is a realistic option

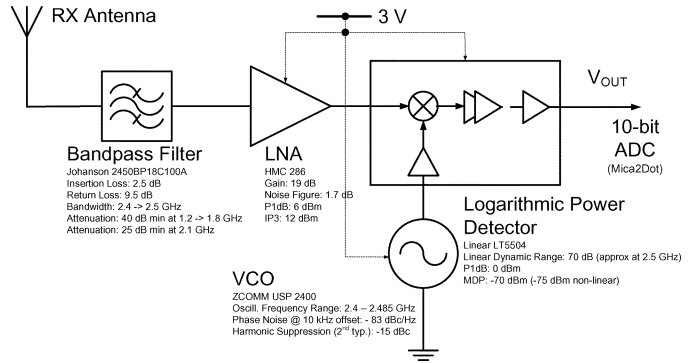


Fig. 3. Block diagram of bodyworn 2.45-GHz data logging receiver front-end. The output voltage V_{out} is proportional to the received signal power in dBm.

for bodyworn applications as it is low-profile, cheap, and simple to manufacture and can be readily integrated into RF circuitry. In this case, the antenna design was optimized by modeling the entire measurement module (including substrates, groundplanes, metal connecting pins, and power supply) at 2.45 GHz using the SEMCAD X FDTD electromagnetic solver. Since the modules are exclusively for bodyworn use, in the FDTD simulation of the system the receiver unit was placed 5 mm above a three layer dielectric flat numerical phantom representing human tissue at 2.45 GHz (skin ($\epsilon_r = 42.86$, $\sigma = 1.59 \text{ Sm}^{-1}$), fat ($\epsilon_r = 10.82$, $\sigma = 0.27 \text{ Sm}^{-1}$), muscle ($\epsilon_r = 53.58$, $\sigma = 1.81 \text{ Sm}^{-1}$) [8]).

During measurements, the logarithm of the received RF signal was converted to a linear dc voltage which was then filtered by a single-pole 100-Hz antialiasing filter. The Mica2Dot device was used to provide 10-bit analogue to digital conversion at 256 samples per second and subsequent storage with an on-board 512-kB EEPROM. Each of the bodyworn modules were individually precalibrated and utilized a proprietary 3-V, low drop-out regulated power supply unit. The bodyworn receiver design was extremely compact with overall module dimensions of 30 mm (length) \times 40 mm (width) \times 10 mm (height). All units were directly fixed (no dielectric spacers or extended groundplanes) to the rescue person's helmet and protective clothing. For robustness, the body to body measurements consisted of a total of 240 000 samples (approximately 4 min of continuous sampling per device). The results were then normalized for statistical analysis which was performed by removing the local mean (10λ). Due to the constricted space and unfamiliarity with the surroundings, rescuer speeds are likely to be relatively slow especially when vision is obscured. For this letter, it was estimated that peak walking speed was a moderate 0.5 m/s giving a maximum relative velocity of 1 m/s (in the case where the transmitter and receivers are moving away from each other in opposite directions). For these speeds, the measurement system had a worst-case resolution of $\lambda/31$ with the sampling rate of 256 Hz.

The principal objective of this study was to carry out an unobtrusive investigation into the typical channel fading characteristics for body-to-body communications. Therefore, no restrictions were placed upon the rescue team's movements or postures so that a realistic representation of fading characteristics of the

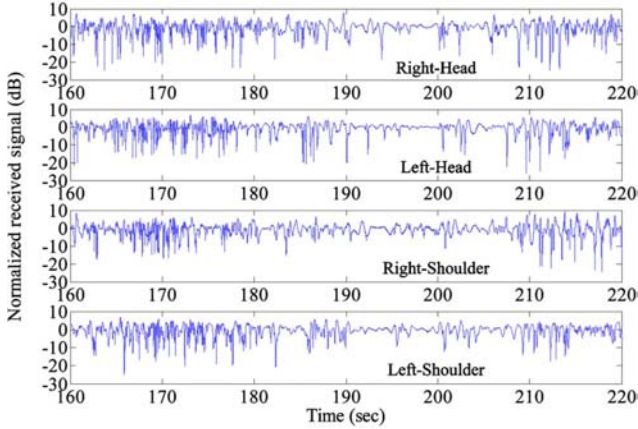


Fig. 4. Time series sample from 160 to 220 s of normalized received signal envelope for all body mounted receivers.

channel was obtained. Hence, channel conditions may have oscillated between LOS and NLOS, and link distances varied considerably throughout the measurements. It is also worth noting that in this type of operation body to body communications are typically contained within a single level of the building. While it is possible that either end of the link may have been situated on a different sublevel (Fig. 1) from each other, the team was always in a group when transferring between major levels.

III. FIRST-ORDER STATISTICS

The κ - μ distribution has recently been proposed as a general fading model which can represent the small-scale signal variation of a fading signal under LOS conditions [7] and may be given in its normalized form as

$$f(\rho) = \frac{2\mu(1+\kappa)^{\frac{\mu+1}{2}}}{\kappa^{\frac{\mu-1}{2}} \exp(\mu\kappa)} \exp[-\mu(1+\kappa)\rho^2] \times I_{\mu-1} \left[2\mu\sqrt{\kappa(1+\kappa)}\rho \right] \quad (1)$$

where $\rho \geq 0$ is the normalized signal level (r/r_{rms}), $I_v(\cdot)$ is a modified Bessel function of the first kind, order v , and $\kappa, \mu > 0$. The κ parameter is defined as the ratio between the total power of the dominant component and the total power of the scattered waves and a moment based estimator is provided as

$$\kappa^{-1} = \frac{\sqrt{2} [E(\rho^4) - 1]}{\sqrt{2E^2(\rho^4) - E(\rho^4) - E(\rho^6)}} - 2 \quad (2)$$

where $E[\cdot]$ denotes the expectation. In a similar fashion, the μ parameter can be estimated as

$$\mu = \frac{1}{\text{var}(\rho^2)} \cdot \frac{1+2\kappa}{(1+\kappa)^2}. \quad (3)$$

The κ - μ distribution contains a number of other distributions as special cases. These include the Rice distribution when $\mu = 1$, in which case the κ parameter coincides with the Rice K factor. When κ is zero, in a similar manner to the Rice pdf, the κ - μ distribution becomes equivalent to the Rayleigh distribution. Another fading model which has been successfully used to describe fading in bodyworn channels [4] is the Nakagami- m distribution

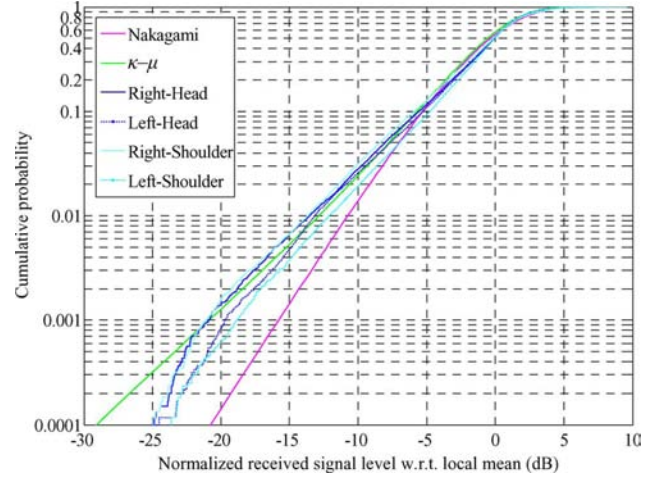


Fig. 5. Theoretical Nakagami ($m = 2.04$, $\Omega = 1.09$), $\kappa - \mu$ ($\kappa = 2.31$, $\mu = 1.19$) and empirical distributions for all body mounted receivers.

[9]. When $\kappa \rightarrow 0$, Yacoub [7] has shown that the $\kappa - \mu$ distribution describes in an exact manner the Nakagami- m density function.

All parameter estimates presented in this paper were obtained using maximum likelihood estimation (MLE) on a 95% confidence interval with the constrained minimization algorithm, `fmincon`(\cdot), available in the optimization toolbox of Matlab, by minimizing the negative log-likelihood function over the bounded parameter space. The initial parameter estimates required by this function were obtained using the moment based estimators given in (2) and (3).

Fig. 4 shows a 1 minute sample of the received signal envelopes for all body mounted receivers, it can be seen quite clearly that fades of up to 10 dB from the local mean are experienced quite regularly when the radio signal is propagating between two mobile bodies in a multipath environment with greater deviations occurring less frequently. The correlation between each of the fading envelopes was also calculated and found to be always less than 0.04. This suggests that the prospects of successfully implementing bodyworn diversity [10] using these antenna locations is extremely good.

In bodyworn applications that involve signal propagation from one mobile user to another, it is likely that specific user movements in conjunction with the physical attributes of the local environment may provide a degree of spatial correlation for the diffuse signal contribution. This suggests that the $\kappa - \mu$ distribution, which assumes a nonhomogeneous scattering environment, is inherently suitable for characterizing these types of channel. Empirical distributions for all receivers are shown in Fig. 5 alongside a general $\kappa - \mu$ distribution obtained by performing MLE on an amalgamated vector of all the normalized measured signal levels. Also included in Fig. 5 is a similarly estimated general Nakagami- m distribution for comparison. All plots are shown with a log-log scale to facilitate careful inspection of the tails of the distributions which are known to determine the bit error rate in marginal radio systems. In all cases, the general $\kappa - \mu$ distribution outperforms the Nakagami distribution for fades below the local mean. For improved accuracy the parameter estimates for the individual channels are

TABLE I
MLE ESTIMATED $\kappa - \mu$ AND NAKAGAMI PARAMETERS FOR ALL
BODY-TO-BODY CHANNELS

Position / Parameter	κ	μ	m	Ω
Right-Head	1.99	1.17	1.95	1.10
Left-Head	2.51	1.11	2.08	1.09
Right-Shoulder	1.26	1.43	1.74	1.11
Left-Shoulder	3.22	1.08	2.33	1.08

provided in Table I. Another notable characteristic of the CDF plots is that the tail of the empirical distribution is above that of the theoretical Nakagami- m plot. Yacoub [7] cites the use of this attribute of the acquired data as a visual test to determine the suitability of the $\kappa - \mu$ distribution compared to another known as the $\eta - \mu$ distribution, also extensively explained in [7], which may be used to describe fading in NLOS channels. The $\kappa - \mu$ distribution is appropriate when the lower tail of the empirical distribution is above the Nakagami- m plot in the fading plane (Fig. 5).

IV. LEVEL CROSSING RATES (LCR)

Another statistic which is useful in the design of mobile radio systems and the analysis of their performance is the LCR. Among its uses is in the design of error correcting codes, optimization of interleaver size and system throughput analysis as well as channel modeling. The expected rate N_R at which the signal envelope crosses a given threshold level in a positive going direction for a $\kappa - \mu$ fading envelope may be written as [11]

$$N_R(r) = \frac{\sqrt{2\pi\mu}f_m(1+\kappa)^{\frac{\mu}{2}}}{\kappa^{\frac{\mu-1}{2}} \exp(\mu\kappa)} \rho^\mu \exp[-\mu(1+\kappa)\rho^2] \times I_{\mu-1} \left[2\mu\sqrt{\kappa(1+\kappa)}\rho \right]. \quad (4)$$

Fig. 6 shows the empirical LCRs and the general $\kappa - \mu$ LCR compared with the general Nakagami LCR [12]. It is evident that all four receivers in this instance experience similar crossing rates in the vicinity of the local mean signal level (typically 4 Hz), slight deviations occurring beyond the -10 dB level. For all empirical LCRs the $\kappa - \mu$ LCR of (4) is shown to provide a substantially improved fit when compared to the Nakagami- m LCR.

V. CONCLUSION

A systematic investigation of the fading characteristics experienced in body to body communications channels for fire and rescue personnel searching a smoke-filled building was presented. In all channels, the $\kappa - \mu$ distribution was shown to provide a good fit for fading levels below the local mean and correlation between fading envelopes found to be low. Empirical level crossing rates were observed to be largely similar and well described by the $\kappa - \mu$ LCR. Finally, $\kappa - \mu$ and Nakagami coef-

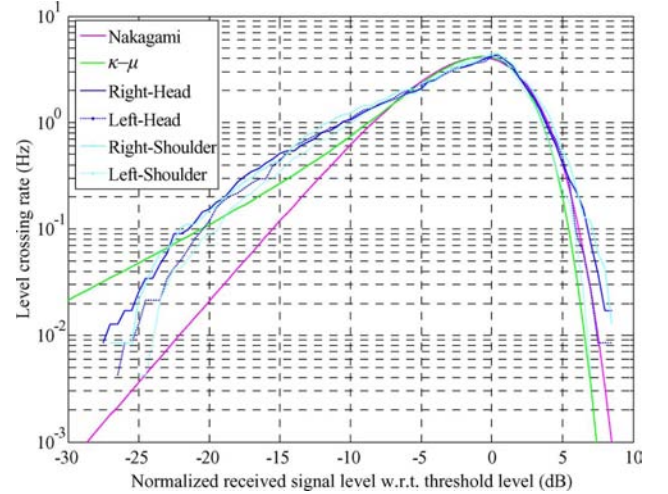


Fig. 6. Theoretical Nakagami ($m = 2.04$, $\Omega = 1.09$, $f_m = 3.98$ Hz), $\kappa - \mu$ ($\kappa = 2.31$, $\mu = 1.19$, $f_m = 5.57$ Hz) and empirical LCRs for all body-mounted receivers.

ficients have been provided for each individual channel so that these results may be reproduced.

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