Channel Measurements in an Open-pit Mine using USRPs: 5G – *Expect the Unexpected*

Rickard Nilsson and Jaap van de Beek

Luleå Univ. of Technology, Dept. of Computer Science, Electrical and Space Engineering, SE-97187 Luleå, Sweden
Rickard.O.Nilsson@LTU.SE, Jaap.vandeBeek@LTU.SE

Abstract—In this paper, we describe and analyze the results of a radio channel measurement campaign in an extreme industrial environment; a large open-pit copper mine targeted by next generation’s highly voiced *device communications*. We present a practical and efficient method to perform robust and high-sensitivity impulse response measurements without a common clock reference using the widely spread USRP hardware. With this technique, we performed channel sounding on a large number of locations within the mine. One important observation is that the radio channel’s impulse response in an open-pit mine can often be more than 10 μ s long, and much unlike the responses normally associated with Wi-Fi and mobile cellular radio systems, which poses serious design challenges for future 5G radio systems.

I. INTRODUCTION

Radio communications systems face a main paradigm shift. Upon decades of sole *human-centric* design, it is today widely acknowledged that *devices* will take a prominent place – key industrial stakeholders project that *billions* of devices, more or less autonomously, will be connected by 2020 [1]. While the initial thrust behind these efforts is made up by applications in the domain of public safety and disaster communications, other, larger forces are looming in the wake of these developments. Large industries are eager to innovate their product lines, processes, logistics, etc. with the help of the advances in radio technology. Massive radio connectivity of all kinds of sensors, actuators, machines and, for instance, cameras are believed to enable efficient process industry, manufacturing industry, logistics, and transport. Clearly, this has implications for the PHY-layer design of future radio systems. Not only are requirements of industrial devices and applications very different from those in consumer applications (latency, robustness, reliability), but new industrial radio nodes are also likely to operate in different places and radio environments than those of today’s typical consumers.

In this paper we assess critical characteristics of such a typical, but largely unforeseen, industrial radio environment. As a case study we investigate the radio channel in one of the industrial environments: *the Aitik open-pit copper mine* in Northern Sweden. While underground mines’ radio channel characteristics have been studied a number of times (see e.g. [2]–[4]) radio characterization, including measured impulse responses, from open-pit mines are largely absent in the open literature.

For this purpose, we developed a practical and novel synchronization technique for correlation-based channel sounding. With the Universal Software Radio Peripheral (USRP) [5] this method yield high dynamic range impulse responses and it is also feasible for underground and indoor

Fig. 1. The Aitik open-pit copper mine. Left: Transmitter site. Right: View over the mine, from the south, with the transmitter position indicated.

measurements where sharing a common clock reference, e.g. with a cable or from GPS satellites, can be challenging.

We report results of our measurement campaign in the Aitik open-pit-mine whose results point at challenges for the design of the physical layer of future 5G machine-type communications (MTC) systems [1]. As a dominant result we show how extraordinary long the channel impulse response can be and show its impact on the achievable spectral efficiency for communications systems with a limited guard interval (GI). Then we discuss some important consequences of these observations both in terms of performance of today’s off-the-shelf systems and for the design of future tailored systems, and finally we summarize our work.

II. RADIO COMMUNICATIONS IN THE AITIK OPEN-PIT COPPER MINE

The Aitik copper mine in Gällivare, situated north of the Arctic Circle in the North of Sweden, is one of the largest open-pit mines in Europe, and operated by Boliden AB. Figure 1 shows a photograph of the bean-shaped open-pit mine that covers an area of about 2.5 km long and 300–700 m wide. Its depth is about 450 m at the deepest location from the rim and its overall geometry is constantly under change. Ton by ton of excavated rock are mined by some of the largest machines and vehicles in the world, which gradually makes the open-pit wider and deeper.

Reliable radio communications is essential in order to increase the efficiency in the mining process. Currently, radio communications is mainly used for the logistics of large vehicles and machines, but in the future remote controlling the mine is foreseen. Wireless communications among trucks, semi-mobile equipment, vehicles, and people in the Aitik open-pit mine is currently being performed through a IEEE 802.11n Wi-Fi network operating in the 2.4 GHz band. However, since Wi-Fi use a guard interval with a duration of only 0.8 μ s (with the standard 20 MHz channel

spacing) [6], this extreme environment is challenging with respect to reliable communications and spectral efficiency as we will show in this paper.

III. CHANNEL SOUNDING TECHNIQUE WITH USRPs

Our measurements were performed in a 25 MHz wide frequency band immediately below to the unlicensed 2.4 GHz ISM band. This part of the spectrum was unused at the time of the campaign so that the channel sounding measurements could be performed relatively undisturbed. A radio transmitter with a 9 dBi Yagi-antenna having a broad main lobe, in both the horizontal and the vertical direction, was placed on the rim of the mine at a spot close to where Boliden's own Wi-Fi access points were located. Figure 1 shows the location and mounting of the transmitter antenna. It was facing slightly down and toward the inner of the mine and connected to a USRP N210 with a low-loss RF cable. Both the transmitter and receiver USRPs were equipped with a SBX RF-board, which covers the 400 MHz to 4400 MHz frequency range, and connected to a laptop computer with Gigabit Ethernet. In this work, the signal transmission and reception was implemented in Gnu Radio [7] while the post-processing steps were performed off-line in Matlab [8].

A. Transmitter

We adopt in a classical manner maximum-length or m -sequences in our measurements, see e.g. [9]. The baseband transmit signal consists of continuously repeating a known m -sequence, $\{a_i\}$, of length $K = 2^m - 1$,

$$x(t) = \sum_i a_{(i \bmod K)} p(t - iT) \quad (1)$$

with $a_i = \pm 1$, and $(i \bmod K)$ represents the remainder (modulo operator) in the range $\{0, \dots, K - 1\}$ of the division i/K . The continuous time pulse-shape $p(t)$, is performed by the internal upsampling and filtering stages in the USRPs FPGA and DAC logic. The discrete autocorrelation function of the m -sequence fulfils

$$r_{aa}[j] = \frac{1}{K} \sum_{i=0}^{K-1} a_i a_{i-j} = \begin{cases} 1, & j = 0 \pmod{K} \\ -\frac{1}{K}, & j \neq 0 \pmod{K}. \end{cases} \quad (2)$$

In our measurements we used a sequence-length of $K=2047$ (with $m=11$) and the sequence elements (chips) were transmitted at a rate of 25 Msamples/s, giving a chip-duration of $T=40$ ns. The same sequence was hence continuously repeated each $KT=81.9$ μ s.

B. Receiver

For the USRP receiver we used a vehicle mounted 7 dBi omni-directional antenna, very similar to the model Boliden are using for Wi-Fi on their trucks. It was placed above the roof of a pick-up car, clearly visible from all directions, and connected to the USRP receiver. At 69 different locations in the mine our receiver recorded baseband signal samples at 25 Msamples/s which were stored at the laptop's SSD. The blue line in Figure 2 shows the route of the car (where merely continuous energy measurements were recorded) while the red dots represents the locations of the wide band measurements for channel sounding which we present

Fig. 2. Transmitter placement on the rim of the pit indicated with the large “T” icon, and 69 dispersed reception locations, “R” icons. The blue curve indicates the route through the pit and the white line represents 1000 m on the ground.

in this paper. At each static receiver location our USRP-based channel sounder receiver captured and recorded five seconds of continuous signal data containing over 61000 repetitive m -sequences.

C. Post processing step 1: Synchronization

Good synchronization is necessary in order to derive high dynamic range channel impulse responses. Only when perfect synchronization is achieved, the autocorrelation in (2) is fulfilled and coherent averaging of multiple impulse responses is possible. Traditional synchronization methods such as Costas Loop [10] are, however, sensitive to strong noise and inter-symbol interference (ISI) making them fragile in channel sounding applications with rich multipath propagation. For this reason we developed a simple but very robust synchronization method based on exploiting the high processing gain in the sounding signal.

We performed our channel sounding recordings when the car was standing still, with least possible movements in the surroundings. The transmitter and receiver USRPs were not synchronized to any common oscillator or clock reference which makes this channel sounding method usable also in underground mines and other indoor environments. With the USRP N210 software radios from Ettus Research [5] this synchronization method works particularly well in relatively stationary environments. It can be extended for sounding time-varying channels, especially if more stable RF-oscillators (such as available GPS disciplined oscillators), are utilized with the USRPs. It can also be extended for MIMO channel-sounding with USRPs, where all coherent antennas at the transmitter (and receiver, respectively) share the same local oscillator.

The principle of the receiver synchronization procedure is depicted in Figure 3. Estimates of the phase offsets are first determined from the unsynchronized baseband signal by correlating against the transmitted m -sequence;

Fig. 3. Channel sounding with USRP transmitter and receiver. The receiver post-processing consists of frequency synchronization and coherent impulse response averaging.

Fig. 4. Stacked sequences of unsynchronized correlator output, $c[n]$, (top). Phases at the peaks for each correlation sequence, $\theta[l]$, (bottom).

$c[n] = r[n] * a_{-n}$, where $*$ represents convolution. This is illustrated by the first block in the lower branch in Figure 3.

Since we were performing channel sounding in a relatively stationary radio-environment, we assumed that the channel impulse response was stationary for short time intervals corresponding to our averaging time, which suggests to be true also in practice since the dynamic range that we achieved essentially reaches the theoretical limit, see Sections III-D and IV. Consequently, when perfectly synchronized the maximum correlation peak

$$c_p[l] = c[lK + p], \quad (3)$$

does not change between consecutive realizations of the sounding signal, where the constant offset p corresponds to the strongest multipath component. Therefore,

$$\theta[l] = \angle c_p[l] = \theta_p \quad \forall l. \quad (4)$$

In our measurements we arbitrary centered p to $0 \mu s$ on the time axes, since we did not measure the absolute signal propagation delays between the transmitter and receiver locations. Next we will exploit the property in Eq. (4) together with the autocorrelation properties in Eq. (2) in our receiver based synchronization procedure.

Figure 4 (top) shows the unsynchronized correlator output, $c[n]$, which is split into parallel the K -samples long sequences indexed by l . Due to the large processing gain, the maximum correlation peak for each sequence, $c_p[l]$, can easily be determined also when the received wide band signal is deeply buried in noise and distorted by

ISI due to the multipath propagation. The peak values, $c_p[l]$, are illustrated by the red dots in Figure 4 (top). While unsynchronized they give accurate estimates of the unknown phase drift $\theta[l]$ since the peaks enjoy the best instantaneous Signal to Interference Noise Ratio (SINR) and appear therefore as the best candidates when taking measurements of the phase drift.

The phase drift can be tracked via the correlation peaks as long as its rate of change is less than Nyquist, determined from the sampling rate by the repetitive sounding sequences, $1/KT$ Hz. Therefore, the m -sequence length (and processing gain) K , need to be selected accordingly, preferable allowing sufficient oversampling of the phase-variations in order to easier overcome noise and other imperfections. However, there is a practical trade-off when selecting K . A higher gain helps to lift the signal from background noise and obtain synchronization. Although with a longer sequence, the phase drift becomes more detrimental on the achievable processing gain before synchronization is established. Furthermore, a lower processing gain helps to track more rapid phase variations, and also to some extent a time-varying channel, but is more sensitive to signal attenuation and noise and therefore also more sensitive to obtain the frequency synchronization.

The bottom part of Figure 4 shows an example of the phase drift, $\theta[l]$, at the repetitive max peak locations. From Eq. (4), in a stationary environment, any phase variations, as illustrated in the bottom part of Figure 4 is a consequence of the relative frequency mismatch between the USRP transmitters' and receivers' RF-oscillators. Thus, we obtain accurate estimates of the rotation caused by the phase offset at the location of each peak for each sequence, l , with

$$e^{j\hat{\theta}[l]} = \frac{c_p[l]}{|c_p[l]|}. \quad (5)$$

The frequency synchronization of the received baseband signal can now be performed with

$$y[n] = \alpha[n]r[n], \quad (6)$$

where $r[n]$ is the received (and appropriately delayed) baseband signal and the rotational coefficients, $\alpha[n]$, are determined by

$$\alpha[n] = \left\{ e^{-j\hat{\theta}[n]} \right\}_{\uparrow K} = \left\{ \frac{c_p^*[n]}{|c_p[n]|} \right\}_{\uparrow K}, \quad (7)$$

where $\{\cdot\}_{\uparrow K}$ represents interpolation with a factor K , and $*$ represents complex conjugation.

D. Post processing step 2: Coherent impulse response averaging

With the frequency synchronized baseband signal, $y[n]$, a renewed step of correlation is performed, see Fig. 3, to achieve a K -periodic sequence of impulse responses

$$\begin{aligned} r_{ya}[n] &= \frac{1}{K} y[n] * a_{-n} = \frac{1}{K} \sum_k y[k] a_{k-n} \\ &= h[n \bmod K] - \frac{1}{K} \sum_{l \neq n \bmod K} h[l] + \frac{1}{K} \sum_{k=0}^{K-1} v[n+k] a_k, \quad (8) \end{aligned}$$

where $h[n]$ is the discrete-time impulse response and $v[n]$ is received additive noise. Now, assuming that the channel remains constant over some coherence time, we coherently average N channel realizations from the correlation sequence above to suppress the filtered additive noise, which is represented by the last term in Eq. (8), and reduce its variance by an additional factor N . Furthermore, notice from Eq. (8) that the processing gain, K , is also the highest possible dynamic range that we can achieve for the impulse response estimates once the additive noise is sufficiently suppressed by the averaging. In our averaging we used $N = 10^4$ sequences, which corresponds to 0.82 s.

IV. MEASUREMENT RESULTS

Four measurement realizations of the impulse response (out of the 69 in the campaign) are shown in top parts of Figure 5 to 8, corresponding to four different locations in the Aitik open-pit mine. Three locations are within the pit. Receiver location #11 is represented by Figure 5; 425 m south, downward from the transmitter. Receiver location #55, see Figure 7; 1000 m south and also downward from the transmitter. Receiver location #66, see Figure 8; 580 m north and 485 m down (deepest point in the mine). Finally, receiver location #40, see Figure 6, is located on the southern rim about 1670 m from the transmitter at approximately the same elevation. Compare also with Figure 2 to determine these receiver locations.

These location samples illustrate typical dispersions of the impulse response that frequently occur. Impulse response dispersions of 10 to 12 μ s (including echoes down to about 40 dB below the strongest echo) are typical for all the measurements we carried out inside the pit (i.e., under its rim) corresponding to top parts of Figures 5, 7, and 8. Note that 1 μ s dispersion corresponds to approximately 300 meter difference in received signal paths. For example, notice one of the characteristic impulse responses in top parts of Figure 5. There, at receiver location #11, its near line of sight to the transmitter which is located above and slightly behind one of the ridges. Therefore strong and diffracted near-direct paths, which first reach the receiver dispersedly within about 1 μ s, are observed. Then it becomes essentially silent for additionally nearly 2 μ s until very strong and widely dispersed echoes reach the receiver, which lasts another 10 μ s. This second very dispersed group of echoes, correspond to be bounced off the wall on the opposite side of the pit, which is roughly 300 m wide (causing round trip travel of about 600 m, which explains the 2 μ s intermediate silence).

On top of the rim, around the bean-shaped open-pit, shorter impulse responses were observed. One example of this is presented in top part of Figure 6, at receiver location #40, where the echoes are weaker compared to the strong first (essentially) direct path. This is because at the top of the rim, the echoes coming from the deep pit below are much more suppressed than the essential direct paths. Still, however, we can see similar length of the dispersion of the impulse response, up to about 14 μ s, before the echoes finally fade away below the correlation floor given by Eq. (8).

In the deepest location of the mine, corresponding to receiver location #66 (see Figure 2), there is no direct line-of-sight to the transmitter, which is located some 485 m steeply above the receiver (and about 580 m to the side) and shadowed by one of the internal rims of the pit. Here also, a very dispersed channel impulse response is encountered, see top part in Figure 8. Interestingly, the strongest path does not correspond to the path with the shortest distance to the transmitter. In the bottom of the pit, you are entirely surrounded by close, steep and stepped walls reaching diagonally more than 500 m up to the top rim, where the transmitter was located but not visible from the bottom of the pit. This is an example of a very extreme environment with an echo-chamber effect that is rarely seen elsewhere.

V. SPECTRAL EFFICIENCY ANALYSIS AND COMMUNICATION CHALLENGES

For all block transmission systems with a Guard Interval (GI), such as OFDM with a cyclic prefix, it is well known that all echoes outside the GI cause ISI between adjacent symbols [9]. We have therefore evaluated the general effects on any system with a too short GI in relation to the actual channel dispersion by calculating the effective SINR and Spectral Efficiency (SE), for different GI lengths.

By assuming a general system with unit transmit signal power and that all received signal power can be utilized, the Signal to Noise Ratio (SNR) is determined by $\text{SNR} = \sum_n |h[n]|^2 / \sigma_v^2$, where σ_v^2 is the average power of additive white Gaussian noise which we vary to form a range of SNRs. Similarly, we calculate the SINR as

$$\text{SINR}(\mathcal{GI}) = \frac{\sum_n |h[n]|^2}{\sum_{n \notin \mathcal{GI}} |h[n]|^2 + \sigma_v^2} \quad (9)$$

where $\mathcal{GI}$ represents the set of guard interval samples. In our analysis it is synchronized relative to the dispersive channel in order to contain the highest possible signal power, while the possibly remaining echoes falling outside the $\mathcal{GI}$ result in ISI. Thus, whenever the GI is longer than the time dispersion of the channel, $\text{SINR}(\mathcal{GI}) = \text{SNR}$.

The spectral efficiency reflects the maximum achievable bit rate efficiency for any communication system with regard to the actual channel conditions, level of ISI (determined by the GI length) and background noise. By assuming that the sum of ISI and background noise is Gaussian, we define the SE as

$$\text{SE}(\mathcal{GI}) = \log_2 \left(1 + \frac{\text{SINR}(\mathcal{GI})}{\Gamma} \right) \text{ [bit/s/Hz]}, \quad (10)$$

where Γ is a system margin accounting for general system imperfections compared to the Shannon capacity limit. In

Fig. 5. Receiver position #11; Impulse response (top), SINR vs. SNR (middle), Spectral Efficiency (bottom). Fig. 6. Receiver position #40; Impulse response (top), SINR vs. SNR (middle), Spectral Efficiency (bottom). Fig. 7. Receiver position #55; Impulse response (top), SINR vs. SNR (middle), Spectral Efficiency (bottom). Fig. 8. Receiver position #66; Impulse response (top), SINR vs. SNR (middle), Spectral Efficiency (bottom).

all our SE plots in this paper we have chosen $\Gamma = 5$ dB. Note however, that we do not take into account for any efficiency losses due to the GI itself, which is a system design issue rather than a radio channel issue. That is, with a long GI a very long symbol duration can be chosen to reduce the additional efficiency loss in the system design.

As we can see in the middle and bottom parts of Figures 5 to 8 a quite long GI is needed to overcome ISI completely. A very short GI equal to $0.8 \mu\text{s}$, as used in most current IEEE 802.11-based Wi-Fi systems, is very detrimental on the reliability at most locations within the mine, see Fig. 5, 7 and 8, except on the ridge of the open-pit with line-of-sight to the transmitter, Fig. 6. Increasing the signal power will not result in any better reliability or efficiency in situations with a too short GI. Because increasing the transmit power results then also in stronger echoes and ISI which effectively limits the SINR and SE performance particularly at higher SNR levels.

In Figures 5 to 8 notice that while the SE performance is considerably better with a GI of $5 \mu\text{s}$, which corresponds to the normal length used in LTE mobile systems [11], it is still not long enough when operating in the high SNR regions, especially when the receiver is located within the open-pit mine where strong and dispersed echoes occur, as illustrated by Fig. 5, 7 and 8.

Due to the strong and dispersed echoes in open-pit mines future 5G communication systems, such as for MTC, need a GI-length of at least $10 \mu\text{s}$ in order to be reliable and have a high efficiency. For a system designer, however, that poses challenges since a long GI should be followed up by a long symbol duration in order to keep the GI-redundancy low. Furthermore, for the wideband signals needed in 5G systems long symbol durations (with many sub-carriers as in the case of OFDM) also introduce challenges with respect to frequency synchronization, Doppler shifts, coherence times, and latencies. However, in open-pit mines these challenges are achievable since the surrounding environment is unusual stationary and the very large and heavy vehicles move just slowly.

VI. SUMMARY

We have performed high dynamic range channel measurements with off-the-shelf USRP software radios in an extreme environment; the large open-pit mine in Aitik located in Northern Sweden.

To be able to perform efficient channel sounding with the USRPs that lacked a common clock reference between the transmitter and receiver, we first developed a practical yet very effective synchronization method. It allowed us to compute high-dynamic range impulse responses from the received and unsynchronized baseband signal.

Then we performed a channel sounding campaign in the Aitik open-pit mine and found that the delay spread of the channel in the 2.4 GHz frequency band is often more than $10 \mu\text{s}$. This raises fundamental challenges when designing reliable industrial 5G-radio systems such as for machine-type-communications. However, with the radio channel knowledge presented in this paper system designers can properly design reliable radio communication systems also for this type of environments.

VII. ACKNOWLEDGMENTS

We thank Lars-Gunnar Marklund, Boliden AB, and Urban Oskarsson, Aitik, along with the financial support through Process-IT-Innovations at LTU.

REFERENCES

- [1] D. Aziz, K. Kusume, O. Queseth, H. Tullberg, M. Fallgren, M. Schellmann, M. Uusitalo, and M. Maternia, "METIS final project report," 7th Framework Programme, Tech. Rep., 2015. [Online]. Available: <https://www.metis2020.com/>
- [2] I. F. Akyildiz, Z. Sun, and M. C. Vuran, "Signal propagation techniques for wireless underground communication networks," *Physical Communication*, vol. 2, no. 3, pp. 167 – 183, 2009.
- [3] K. A. Qaraqe, S. Yarkan, S. Güzelgöz, and H. Arslan, "Statistical wireless channel propagation characteristics in underground mines at 900 MHz: A comparative analysis with indoor channels," *Ad Hoc Networks*, vol. 11, no. 4, pp. 1472 – 1483, 2013.
- [4] A. Forooshani, S. Bashir, D. Michelson, and S. Noghanian, "A survey of wireless communications and propagation modeling in underground mines," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 4, pp. 1524–1545, March 2013.
- [5] Ettus Research. [Online]. Available: www.ettus.com
- [6] "IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std 802.11-2012 (Revision of IEEE Std 802.11-2007)*, pp. 1–2793, March 2012.
- [7] Gnu Radio. [Online]. Available: www.gnuradio.org
- [8] Matlab. [Online]. Available: www.mathworks.com
- [9] A. F. Molisch, *Wireless Communications*, 2nd ed. Wiley, 2010.
- [10] J. Costas, "Synchronous communications," *Proceedings of the IRE*, vol. 44, no. 12, pp. 1713–1718, Dec 1956.
- [11] "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (Release 13)," *3GPP TS 36.211 V13.0.0 (2015-12)*, pp. 1–141, Dec 2015.