Digitising VHF FM sound broadcasting with DRM$^+$ (DRM Mode E)

Aspects related to compatibility, coverage and radio network planning

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***Abstract*—This paper summarizes and discusses findings on compatibility of the forthcoming DRM mode E into classical VHF FM sound broadcasting. The results are based on theoretical considerations, lab measurements, field trials and radio network planning exercises. In addition, the status of the ongoing work towards a comprehensive DRM mode E coverage study including first results hereof are given.**

I. Introduction

Digital Radio Mondiale™ (DRM) is a digital broadcasting system for the broadcasting bands below 30 MHz. It is standardised as ETSI ES 201 980 [1] and has been adopted by the ITU. The DRM consortium is about to extend DRM to the broadcasting bands up to 120 MHz [2] by including the new mode 'E', referred to as 'DRM$^+$' in this paper. Table I summarises the key parameters of DRM$^+$.

TABLE I: DRM$^+$ key parameters at a glance [2]

Parameter	Value
Net MSC data rate range	37-186 kbit/s
Audio coding	MPEG4 AAC plus
# of channels / service	1-4
Symbol duration without guard interval	2.25 ms
Guard interval duration per symbol	0.25 ms
# of carriers per symbol	213
Subcarrier spacing	444 4/9 Hz
TF duration	100 ms
# of symbols per transmission frame (TF)	40
# of TFs per transmission super frame	4
Subcarrier modulation	4/16 QAM
RF system bandwidth	96 kHz

Throughout March to May 2008, the University of Applied Sciences of Kaiserslautern has broadcast and received two experimental radio stations across this south-western German city on 87.6 MHz (FM and DRM$^+$) and 87.6 – 87.9 MHz (FM). The focus of first broadcasting period ('1st field trial') laid on validating and extending the results on *compatibility* with the analogue FM system previously obtained from exhaustive lab measurements [3]. Furthermore, first impressions on DRM$^+$ coverage using the very first real time DRM$^+$ prototype receiver worldwide could be obtained during the 1st field trial.
Since a systematic evaluation and assessment of DRM$^+$ *coverage* in real interference limited environments is still outstanding, an additional broadcasting period in the 2nd quarter of 2009 ('2nd field trial') is being prepared. Prior to starting the 2nd field trial, the following work shall be accomplished:

- calibrate the complete DRM$^+$ chain,
- measure the protection ratios FM into DRM$^+$ (FM$\mapsto$DRM$^+$),
- define an appropriate field test setup incl. measurement paradigms.

Like in 2008, the 2nd field trial shall be driven to validate and to extend the lab results obtained from the activities listed above. Both lab and field measurements target on:

- elaborating statements on DRM$^+$ *coverage*,
- proposing *planning paradigms* for DRM$^+$.

These items are of primordial interest when it comes to deploying DRM$^+$ stations into the actually congested VHF FM band.
The paper's outline is as follows: In Sec. II, key outcomes of the 1st field trial and conclusions are given. First results from the present, still ongoing work along with the setup of the upcoming 2nd field trial are presented and discussed in Sec. III. A short outlook in Sec. IV closes the paper.

TABLE II: TX characteristics. All geographical data is noted as WGS-84 data on the WGS-84 ellipsoid.

TX short name	TX FH	TX RB
TX location	49°27′2”N 7°45′47”E	49°27′34”N 7°46′16”E
Modulation	FM stereo or DRM$^+$	FM stereo
Center frequency	87.6 MHz	87.6 MHz . . . 88.1 MHz
ERP (RMS)	35 W	35 W
Antenna	ND	D, 4-element Yagi
Antenna height	30 m agl	30 m agl
Polarization	vertical	vertical

II. 1st field trial March - May 2008

A. Setup

Measurement procedures to determine *lab* compatibility between radio services can not be translated into the real radio environment, i. e. *field* compatibility. Therefore, DRM$^+\overset{\pm}{\mapsto}$FM field compatibility is assessed by *comparing* the *audio quality degradation* perceived by an FM receiver being interfered by either DRM$^+$ or conventional FM. A hybrid transmitter (TX) capable of radiating either DRM$^+$ or conventional FM on 87.6 MHz was set up, cf. Tab. II, denoted as TX FH. The schematic of the hybrid TX FH is shown in Fig. 1. In the context of compatibility DRM$^+\overset{\pm}{\mapsto}$FM, TX FH acts as 'interfering' TX, i. e. generates a controllable 'interfering' signal. FH TX's power density spectrum complies with the ETSI FM spectrum mask [4] for both FM and DRM$^+$. The FM signal whose quality is intentionally degraded by the interfering signal is provided by TX RB. This 'useful' FM signal carries audio test signals to rate the demodulated audio quality.

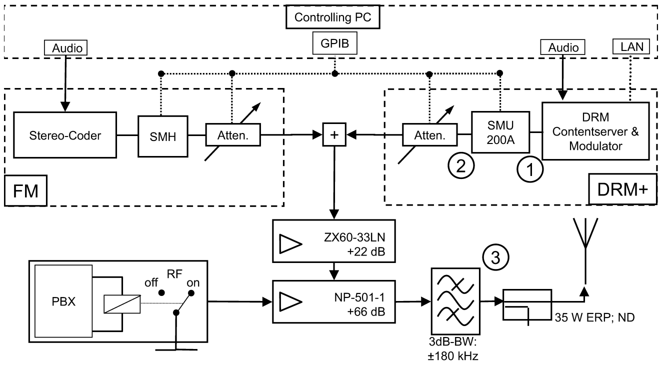

Fig. 1: Schematics of the hybrid FM-DRM+ TX FH (simplified).

B. Measurement paradigm

The regulatory procedures of verifying nominal FM field compatibility as stated in [5] always yield the same outcome as long as the received interfering RF power is the *same*, irrespective of modulation, RF amplitude variations etc. of *any* interfering signal. Consequently, no information about audio quality can be deduced from this measurement approach. Therefore, the following measurement principle was applied: In a given receiving location, the RF signal at the receiver's (RX) input is assumed to be made up of three uncorrelated parts: the useful FM signal, the interfering signal (either FM or DRM+) with frequency offset Δf, and the inevitable background noise signal, accounting for co-channel interferers and other components. Their respective *in-band* RMS powers, measured in a bandwidth of ±60 kHz around the center frequency of useful signal, are denoted as P_V, $P_\mathrm{I}(\Delta f)$, and P_N, respectively. The $\mathrm{SNR}_\mathrm{RF}^\mathrm{FM}$ at the RX's input is a function of Δf, i. e.

$$\mathrm{SNR}_\mathrm{RF}^\mathrm{FM}(\Delta f) = \frac{P_\mathrm{V}}{P_\mathrm{I}(\Delta f) + P_\mathrm{N}}. \quad (1)$$

In (1), the absolute value of frequency offset $|\Delta f|$ takes on the values $[0, 100, 200, 300]\,\mathrm{kHz}$. Varying $P_\mathrm{I}(\Delta f)$ from $0 \ldots P_{\mathrm{I,max}}(\Delta f)$ bounds $\mathrm{SNR}_\mathrm{RF}^\mathrm{FM}(\Delta f)$, i. e. RX input dynamics:

$$\frac{P_\mathrm{V}}{P_\mathrm{N}} \le \mathrm{SNR}_\mathrm{RF}^\mathrm{FM}(\Delta f) \le \frac{P_\mathrm{V}}{P_{\mathrm{I,max}}(\Delta f) + P_\mathrm{N}}. \quad (2)$$

Three measures were used to assess audio quality, namely

- psophometrically weighted (S/N) [6],
- SINAD [7] and
- Audemat quality class (AQC) [8].

All these measures express audio quality; the higher the value, the better the quality. (S/N) and SINAD have *metric* scaling and are often given on a Decibel scale, whereas AQC $\in [1, 2, 3, 4, 5]$ is *ordinally* scaled. (S/N) and SINAD were recorded in 18 locations for stationary reception using a setup based on [5]. For mobile reception, SINAD and AQC values were collected with geographical reference along a route of approx. 40 km length. For each measurement, $\mathrm{SNR}_\mathrm{RF}^\mathrm{FM}$ according to (1) and the audio qualities were measured as a function of Δf and interfering modulation type (FM or DRM+). Doing so allows (a) linking $\mathrm{SNR}_\mathrm{RF}^\mathrm{FM}$ to audio quality and (b) comparing the effect of the interfering modulation type on audio quality[1].

[1]Since a FM reference receiver does only exist as hypothetical model [9], quality depends on the concrete receiver. To circumvent this fact, a receiver whose (S/N) sensitivity performance fairly matches the underlying protection radio curves [10] was used to measure (S/N) and SINAD figures, whereas the Audemat system comes along with an internal receiver.

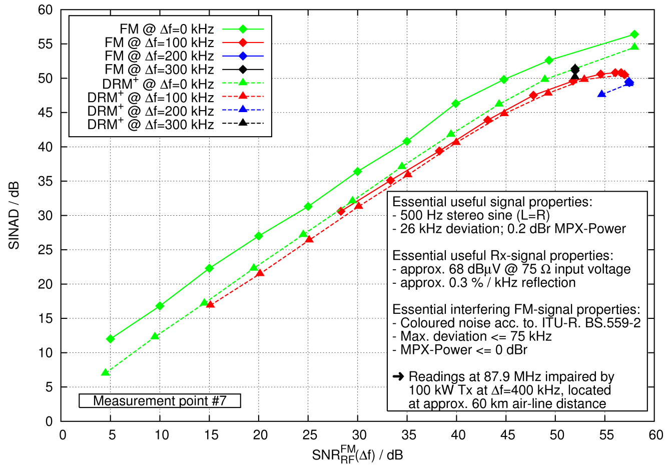

Fig. 2: SINAD over $\mathrm{SNR}_\mathrm{RF}^\mathrm{FM}(\Delta f)$ as a function of $P_\mathrm{I}(\Delta f)$.

C. Results

1) Stationary measurements: An instructive example of the evaluation of measurement data collected from stationary reception is presented in Fig. 2. The curves presented in Fig. 2 display SINAD vs. $\mathrm{SNR}_\mathrm{RF}^\mathrm{FM}(\Delta f)$; curves of similar colour denote similar Δf of the interfering signal with RX power $P_\mathrm{I}(\Delta f)$. The interfering modulation type can be distinguished by the symbols ♦ (FM) and ▲ (DRM+). For each curve in Fig. 2, the leftmost point is defined by $P_{\mathrm{I,max}}(\Delta f)$ (i. e. a TX FH power of 45 dBm), whereas the rightmost point of each curve is defined by $P_\mathrm{I}(\Delta f) = 0\,\mathrm{W}$ (i. e. TX FH switched off). The points in between correspond to a reduction of $P_\mathrm{I}(\Delta f)$ in 5 dB steps whilst keeping P_V constant. Inspecting Fig. 2 suggests that the influence of $P_\mathrm{I}(\Delta f)$ on SINAD decreases with increasing Δf. Furthermore, it follows that DRM+ has a slightly higher interference potential as FM in the co-channel (green curves). For a given SINAD value, $P_\mathrm{I}(\Delta f)$ can be higher for FM than for DRM+. The converse also holds: For a given $\mathrm{SNR}_\mathrm{RF}^\mathrm{FM}(\Delta f)$, FM yields a better SINAD than DRM+. Note that the two green curves are not congruent; this discrepancy clearly indicates the effect of the interferer's modulation type on SINAD. In contrast to the DRM+ interfering signal, the FM modulated interfering signal shows no significant amplitude variations.

2) Mobile measurements: Next, a representative result of mobile recordings is presented and discussed. Referring to Fig. 3, the green, yellow and red pixels along the route denote the *difference* of *median* SINAD values at the same location, $\mathrm{SINAD}_\mathrm{FM} - \mathrm{SINAD}_{\mathrm{DRM+}}$, quantised as follows: $(-\infty, -6\,\mathrm{dB}\,[\mathrm{green}]]$, $(-6\,\mathrm{dB}, 6\,\mathrm{dB}\,[\mathrm{yellow}]]$, $(6\,\mathrm{dB}, \infty\,[\mathrm{red}])$. The results given in Fig. 3 describe the situation encountered along the route when the 'interferer' TX FH operates at 87.6 MHz and 'useful' TX RB at 87.8 MHz, i. e. $\Delta f = 200\,\mathrm{kHz}$, both radiating with full power. As can be seen from Fig. 3, DRM+ and FM seem to be equivalent in terms of interference potential since the yellow pixels clearly dominate along the route, as could be expected from the stationary measurements. An exception is the vicinity of the interfering TX FH, where the dominating interfering signal is very strong as compared to background noise ($P_{\mathrm{I,max}}(\Delta f) >> P_\mathrm{N}$) and the DRM+ amplitude variations result in a lower $\mathrm{SINAD}_{\mathrm{DRM+}}$ value as compared to $\mathrm{SINAD}_\mathrm{FM}$.

3) FM quality criteria correlation: Another example of measurement evaluation is the correlation analysis of the quality criteria (S/N)/ dB, SINAD/ dB and Audemat Quality Classes (AQC). For stationary reception, $\{(S/N); \mathrm{SINAD}\}$ pairs were statistically tested

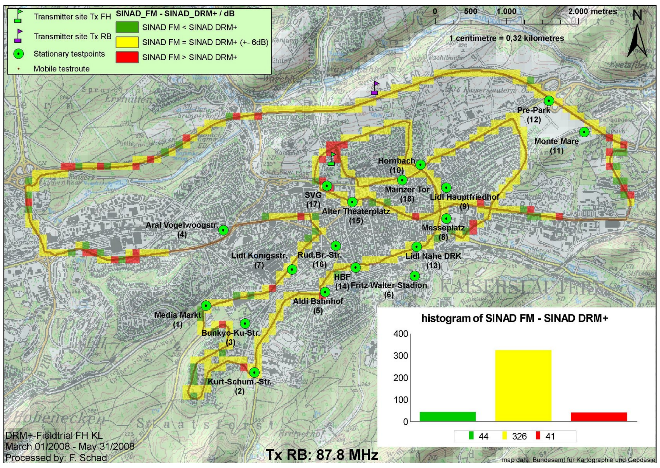

Fig. 3: TX locations, route for mobile measurements and differences of median SINAD values by switching the interfering modulation at TX FH for Δf = 200 kHz.

on linear relationship (linear regression analysis [11, pp. 105] and correlation test [11, pp. 523]) for all frequency offsets Δf. For a 5 % level of significance, the hypothesis '(S/N) and SINAD are *uncorrelated*' must be discarded in all cases. Choosing a 0.1 % level of significance, this hypothesis must be discarded in all cases $\{(S/N)$; SINAD$\}$ except one. The results proposes that $\{(S/N)$; SINAD$\}$ are *correlated*, which is not really surprising if the complete TX/RX chain is operated in its *linear range*. The converse also holds: If $\{(S/N)$; SINAD$\}$ are correlated, then the TX/RX chain is – more or less – linear.

For the mobile recordings, the metric SINAD values were first quantized into five ordinally scaled SINAD quality classes (SQC). Then, the pairs {AQC; SQC} were subjected to a χ^2 independence test [11, pp. 519] and a test based on Spearman's correlation coefficient [11, pp. 525]. Both tests, evaluated for a 0.1 % level of significance, strongly suggest that the correlation between {AQC; SQC} ratings is statistically *highly significant*.

4) Radio network planning exercises: To get an idea on technical conditions allowing for the introduction of 'digital' TX stations into the European VHF FM band relying on *legal radio regulations and coordination procedures*, computer based compatibility and coverage *predictions* for a VHF TX with DRM$^+$ using a specialized version of the frequency and network planning software 'FRANSY' [12] were made. Planning is based on protection ratios (PR), a PR being defined as the minimal difference in RF RX powers (expressed in dB) between a *useful signal* and an *interfering signal* with frequency offset Δf. The PR curves used for the analyses are (a) standardized (FM↦FM), (b) rely on results obtained from the 1st field trial (DRM$^+$↦FM) and (c) theoretical considerations (FM↦DRM$^+$).

From the PR curves, the following conclusions for the (mutual) interference potential of DRM$^+$ and FM can be drawn :

- DRM$^+$↦FM: As compared to an FM interfering signal, a DRM$^+$ signal produces more interference in the co-channel and in the 1st adjacent channel (each ≈ 5 dB more), but substantially less interference starting from $\Delta f > \pm 200$ kHz.
- FM↦DRM$^+$: As compared to a FM useful signal, a DRM$^+$ useful signal is interfered substantially less in the co-channel and in the 1st adjacent channel – i. e. the PR is at least 19 dB smaller – and, starting from $\Delta f > \pm 200$ kHz, interference is negligible.

The planning exercises evaluated two scenarios: (a) replacement scenario (RS), i. e. *replacing* an existing FM TX by a DRM$^+$ TX, and (b) an integration scenario (IS), i. e. *integrating* a *new* DRM$^+$ TX into the existing TX landscape.

The results obtained from the *interference and compatibility analyses* for RS suggest that, in general, a FM TX can be replaced by a DRM$^+$ TX by lowering the ERP by 5 dB to protect the existing FM networks[2]. As for IS, integration of new DRM$^+$ TX is only feasible with rather low ERP as compared to ERP's typically used for FM.

The *coverage prediction analyses* accounted for the 20 strongest FM interferers. For RS, calculations have been carried out based on the assumption that compatibility of a DRM$^+$ TX is established by reducing ERP by 5 dB to protect existing FM stations. The outcomes suggest that the predicted coverage of a DRM$^+$ TX is much better as compared to the predicted coverage of the former FM TX, in spite of power reduction. This effect stems from the lower PR FM↦DRM$^+$, resulting in a lower value of usable field strength, and, as a consequence, in a lower interference impact. For IS, a rather 'good' coverage – as compared to FM – can locally be achieved even with low TX powers.

D. Conclusions

The findings from the 1st field trial propose:

1) DRM$^+$ field compatibility is much easier achieved as lab compatibility.
2) DRM$^+$ signals feature different amplitude statistics as compared to FM signals (CCDF, crest factor) leading to (a) a higher intermodulation potential in the front end of typical FM receivers, and (b) a stronger degradation of perceived FM audio quality. Therefore, a DRM$^+$ signal has an inherently higher absolute interference potential.
3) The psophometrically weighted audio (S/N) of 50 dB, which is the quality criterion for the planning standards for FM sound broadcasting networks, is merely achieved in real world reception conditions.
4) Provided proper bandpass filtering at the TX output, the outcomes propose that – as compared to FM to achieve compatibility – for
   - Δf = 0 kHz, DRM$^+$ power needs to be lowered by ≈5 dB,
   - Δf = ±100 kHz, DRM$^+$ power needs to be lowered by ≈ 5...15 dB, depending on the absolute value of the interference power (higher interference power means higher reduction),
   - Δf = ±200 kHz, DRM$^+$ power needs to be lowered, too, but the perceived audio quality is already good,
   - $\Delta f > \pm 200$ kHz compatibility is not an issue.
5) In the vicinity of a DRM$^+$ TX, where the DRM$^+$ signal strength typically dominates the received signal, the interference potential of DRM$^+$ is generally higher as compared to FM.
6) All three objective measures (S/N), SINAD and AQC are well suited to rate FM audio quality. For mobile measurements, only SINAD and AQC are reasonable. SINAD measurements require a permanent test tone to be transmitted by a station, whereas AQC values can be obtained from a station's regular 'on air' program signal.
7) The introduction of a new DRM$^+$ TX into the existing VHF FM environment involves high or even insurmountable barriers if planning is done in line with the old, but still legal ITU planning

[2] Which FM broadcaster would opt for this scenario in an early stage of digitising the VHF FM band?

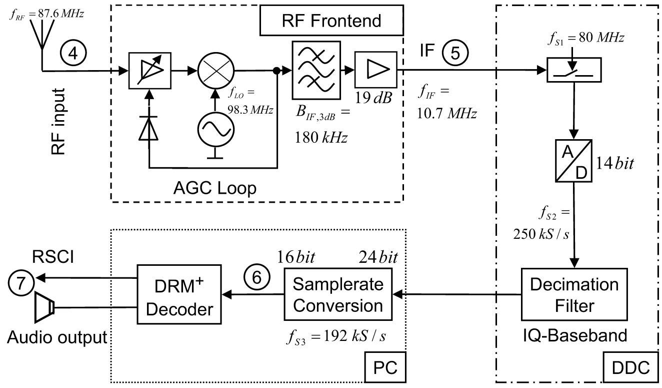

Fig. 4: Block Schematics of the DRM+-Receiver (simplified). The AGC loop incorporates both narrow- and wideband regulation separately.

recommendations applicable for FM systems. To facilitate the introduction of any 'digital' TX station into the FM band, the ITU planning recommendations need to be revised in such a way that today's real FM world is reflected properly: (a) improved FM receivers, (b) lower audio dynamic due to audio compression, and (c) mobile and portable reception.

For a detailed presentation and discussion of all measurements and analyses derived from the 1st field trial, the reader is referred to [13]–[15].

III. 2nd FIELD TRIAL APRIL - MAY 2009

A. Preparatory work

To distinguish between effects on DRM+ quality that stem from the real radio channel from those related to TX/RX impairments, TX/RX characteristics influencing DRM+ quality need to be identified and determined. In addition, knowledge about TX/RX restrictions is mandatory to estimate DRM+ performance in real environments and to design DRM+ coverage criteria that are – ideally – independent from the concrete hardware used.

1) Assessing characteristic data of the TX chain: The most important TX parameters affecting DRM+ quality are (a) linearity and (b) phase noise. Linearity is typically expressed by the output intercept-point of 3rd order, OIP3, which – in case of DRM+ – is related to the output power, P_{out}, and the shoulder distance, S,

$$S/\,\mathrm{dB} \approx 2\cdot(\mathrm{OIP3}/\,\mathrm{dBm} - P_{\mathrm{out}}/\,\mathrm{dBm}) - 2.5\,\mathrm{dB} \qquad (3)$$

as found by simulation and supported by theoretical considerations [16]. At reference point ③, cf. Fig. 1, an OIP3 of circa $60\,\mathrm{dBm}$ was obtained by a two tone measurement with two single carriers spaced by $444\,4/9$ Hz, cf. Tab. I, at maximum allowed output power. To verify the result, S was determined directly from the output DRM+ spectrum to be about $26\,\mathrm{dB}$, confirming (3).

The TX phase noise was found to be $-90\,\mathrm{dBc/Hz}$ at reference point ③ in an carrier offset of the subcarrier spacing, i. e. $444\,4/9$ Hz, which rapidly decreases down to $-110\,\mathrm{dBc/Hz}$ in an offset of three times $444\,4/9$ Hz and beyond.

2) Assessing characteristic data of the RX chain: The schematics of the prototype DRM+ RX used is shown in Fig. 4. It consists of an automotive multi-band, multi-standard RF front end, a digital down converter (DDC), and the IIS real time prototype software decoder. The RF front end shifts the signal from $87.6\,\mathrm{MHz}$ (RF domain, reference point ④) to $10.7\,\mathrm{MHz}$ (IF domain, reference point ⑤). The DDC (a) samples the IF signal with a rate of $f_{\mathrm{s1}} = 80\,\mathrm{MHz}$ using 14 bits of resolution, and (b) down converts it to the complex baseband (IQ domain) whilst decimating to a rate of $f_{\mathrm{s2}} = 250\,\mathrm{kS/s}$. The IQ samples are streamed with 24 bit of resolution via USB to a PC running a real time polyphase resampler. At it's output (reference point ⑥), the sample rate is $f_{\mathrm{s3}} = 192\,\mathrm{kS/s}$ with 16 bit resolution as required by the subsequent IIS software decoder. Note that, as of today, the DDC is not included in the AGC loop, and the scaling of the signal's gain at reference point ⑥ is set manually. Finally, the received MSC streams are output (reference point ⑦) to either loudspeakers or an application via the RSCI-protocol [17].

RX DRM+ quality is mainly influenced by linearity and phase noise, too. The RF front end's overall gain (③↦④) has been set to low $19\,\mathrm{dB}$ to ensure linearity and to avoid clipping at the DDC's input. For RF input power levels $>\approx -50\,\mathrm{dBm}$, the shoulder distance S never gets worse than $54\,\mathrm{dB}$ (connecting reference points ②↦④ and measuring S at reference point ⑤). For RF input power levels $> -15\,\mathrm{dBm}$, the AGC starts to decrease this overall gain without noticeable loss of linearity. RX IP3 measurements at reference point ⑥ are still outstanding.

The RX phase noise at reference point ⑥ was found to lie in the interval $[-90\,\mathrm{dBc/Hz}\ \ldots -85\,\mathrm{dBc/Hz}]$ in $\pm 1\,\mathrm{kHz}$ carrier offset (near carrier phase noise). The maximum phase noise of $\approx -75\,\mathrm{dBc/Hz}$ occurs at carrier offsets of $\approx 1.5\,\mathrm{kHz}$.

An important parameter related to coverage is the RX's sensitivity. The latter is determined by the noise figure. Operating with $19\,\mathrm{dB}$ gain, the overall noise figure (④↦⑥) was found to be $\approx 11\,\mathrm{dB}$.

3) AWGN performance: Three types of measurements shall be used to assess DRM+ performance figures, e. g. *average* bit error rate, $\overline{\mathrm{BER}}$, and *average* rate of successful MSC frame decoding, $\overline{\mathrm{MSC\text{-}FDR}}$, for the AWGN channel:

- M1: Offline baseband simulation.
- M2: Hardware-in-the-loop (HITL) measurements by connecting reference points ② and ④.
- M3: HITL measurements by connecting reference points ③ and ④.

M1 evaluates the pure AWGN $\overline{\mathrm{BER}}$ and $\overline{\mathrm{MSC\text{-}FDR}}$ performance of the decoder including all channel estimation and synchronisation impairments. In addition, M2 and M3 include hardware effects: M2 demonstrates the RX's influence on performance, and M3 gives the overall performance. For both M2 and M3, the SMU200A's internal AWGN channel simulator was used. The RX input power level (reference point ④) was kept constant at $-45\,\mathrm{dBm}$ to ensure operation substantially above the receiver's noise for both M2 and M3.

First results obtained from M1–M3 for 4 QAM (SDC code rate 0.25, MSC code rate 0.4) and 16 QAM (SDC code rate 0.25, MSC code rate 0.33) are presented in Fig. 5. The solid curves display $\overline{\mathrm{BER}}$ (left ordinate) vs. *in-band* $\mathrm{SNR}_{\mathrm{Dec}}$ (defined at reference point ⑥) for 4 QAM (blue) and 16 QAM (red), respectively. Measurement types M1, M2 and M3 are distinguished by the symbols ▾, ▴ and ◆, respectively. The dashed curves link $\overline{\mathrm{MSC\text{-}FDR}}$ (right ordinate) to in-band $\mathrm{SNR}_{\mathrm{Dec}}$ for 4 QAM (blue) and 16 QAM (red) in the case of measurement type M3. Note that *all* curves are based on MSC *synchronous PRBS mode*, i. e. successful MSC frame decoding is a prerequisite for calculating BER.

Inspecting Fig. 5 reveals the typical 'waterfall'-like behaviour of $\overline{\mathrm{BER}}$. Asking for the performance degradation introduced by the RX/TX chain, Fig. 5 suggests that the RX front end and the DDC account for $\approx 0.5\,\mathrm{dB}$ (4 QAM) and $\approx 1.5\,\mathrm{dB}$ (16 QAM), whereas the TX part – operating at full power – contributes another $\approx 0.5\,\mathrm{dB}$ (4/16 QAM). Taking $\overline{\mathrm{BER}} = 10^{-4}$ as criterion, for the overall

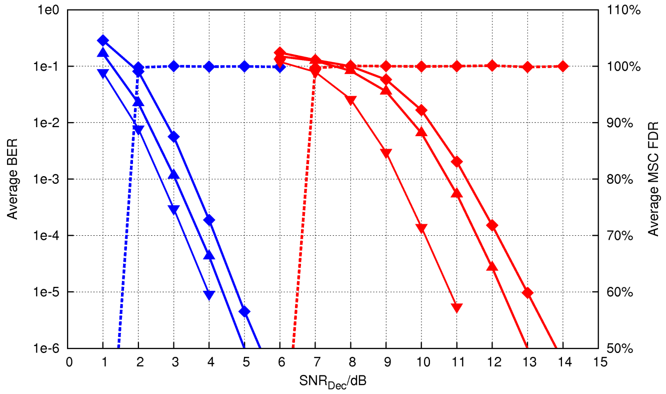

Fig. 5: Left ordinate: AWGN $\overline{\mathrm{BER}}$ performance for 4 QAM (solid blue lines) and 16 QAM (solid red lines) for measurements of type M1 (▾), M2 (▴) and M3 (◆). Right ordinate: AWGN $\overline{\text{MSC-FDR}}$ performance for 4 QAM (dashed blue line) and 16 QAM (dashed red line) for measurements of type M3 (◆). DRM+ code rates used: SDC: 0.25 (4/16 QAM); MSC: 0.4 (4 QAM), 0.33 (16 QAM).

performance (M3), a minimum $\mathrm{SNR_{Dec}}$ of ≈4 dB (4 QAM) and ≈12 dB (16 QAM) is needed.

Looking at the $\overline{\text{MSC-FDR}}$ curves reveals that the $\mathrm{SNR_{Dec}}$ transition interval between completely unsuccessful/successful MSC frame decoding lies in the order of ≈1 dB, i. e. is rather small, which is typical for 'digital' transmission schemes. The DRM+ RX 'starts working' with ≈2 dB (4 QAM) and ≈7 dB (16 QAM), however, its $\overline{\mathrm{BER}}$ performance is very poor.

$\overline{\mathrm{BER}}$ can be interpreted as *expectation* of the *random variable* BER. From the simulation data acquired, approximate quantiles can be derived as further meaningful figures, e. g. $0.9 = P(\mathrm{BER} \le \mathrm{BER}_{0.90})$, giving the *outage probability* $P_{\mathrm{Out}} = 1 - P(\mathrm{BER} \le \mathrm{BER}_{0.90}) = 0.1$. As an example, Tab. III displays approximate quantiles BER_{50}, $\mathrm{BER}_{0.90}$, $\mathrm{BER}_{0.95}$ and $\mathrm{BER}_{0.99}$ obtained from M3. For the sake of comparison, $\overline{\mathrm{BER}}$ is given, too. For $P_{\mathrm{Out}} = 0.01$, i. e. the $\mathrm{BER}_{0.99}$ quantile, $\mathrm{SNR_{Dec}}$ needs to be ≈5 dB (4 QAM) and slightly greater than ≈13 dB (16 QAM), respectively, to ensure $\mathrm{BER} \le 10^{-4}$ with probability 0.99.

TABLE III: Approximate AWGN quantiles derived for 4 QAM and 16 QAM (M3). Note that '—' means that the quantile is so small that it could not be derived by simulating 20 min of real transmission time.

Modulation	4 QAM			16 QAM		
$\mathrm{SNR_{Dec}}$	3 dB	4 dB	5 dB	11 dB	12 dB	13 dB
$\mathrm{BER}_{0.50}$ /‰	5.2	—	—	1.8	—	—
$\mathrm{BER}_{0.90}$ /‰	10.0	0.7	—	4.0	0.6	—
$\mathrm{BER}_{0.95}$ /‰	14.0	1.3	—	5.0	0.9	—
$\mathrm{BER}_{0.99}$ /‰	99.0	2.0	0.1	6.3	1.7	0.4
$\overline{\mathrm{BER}}$/‰	5.7	0.19	0.005	2.0	0.15	0.01

The decoder's performance for M2 and M3 depends on the manual gain control setting at reference point ⑥. Therefore, an adaptive gain control loop must be implemented in order to optimize decoder performance under multipath conditions.

4) Multipath performance: In [2], several multipath scenarios are defined for DRM+ system evaluation. First simulations to get an idea of performance under multipath conditions suggest that DRM+ is sensitive to flat fading. The DRM+ system's bandwidth is rather small, thus, all multipath components lying within a 10 µs interval join to a *single fading path* from the decoder's perspective. Hence it is not surprising that, in these scenarios, DRM+ can not benefit from the radio channel's frequency selectivity, i. e. DRM+ runs through deep fades. This aspect needs to be considered when it comes to defining planning criteria, e. g. by appropriate fading margins.

Potential remedies to this problem are the use of (a) TX diversity as it is proposed for DRM in the short wave band [18] and/or (b) SFN networks with TX site distances not larger than ≈75 km, according to the guard interval duration.

5) Protection ratios: The concept of PRs is always based on a defined *quality* in the sense of 'working properly'. In contrast to FM PRs, for DRM+, no standardized measurement procedures or quality criteria are defined yet. Therefore, the crucial starting point is the 64$ question: what exactly *means* 'working properly'?

In DRM, two criteria technically reflecting 'working properly' are commonly used: (a) $\overline{\mathrm{BER}} \le 10^{-4}$ based on PRBS sequences (Out-of-service measurement), cf. Fig. 5, and (b) average audio frame CRC error rate ≤ 2% (In-service measurement) [19, p. 351]. Thus, a simple, straight forward and pragmatic approach for measuring the PRs is to rely on at least one of these two quality measures, e. g. as follows: First, the useful DRM+ signal is fed to the RX with an appropriate input power level. Next, the interfering signal (either FM or DRM+) is added in a defined frequency offset Δf, and it's power is adjusted to yield $\overline{\mathrm{BER}} = 10^{-4}$. The upcoming PR measurements FM↦DRM+ and DRM+↦DRM+ will be – at least at first – based on this approach. A more sophisticated approach defining PRs could e. g. account for multipath reception scenarios, subjecting (a) only the useful signal or (b) useful and interfering signal to defined multipath profiles, steadily increasing measurement complexity.

B. Setup

For the sake of comparability, the 1st field trial's setup will be used, cf. Sec. II-A: the difference is that the roles of the TXs are interchanged, i. e. reception quality of the 'useful' TX FH will be investigated as a function of TX RB's 'interfering' FM signal and overall background noise.

C. Measurement paradigm

DRM+ coverage shall always be rated *relative* to FM coverage. This is achieved by switching the modulation of TX FH whilst keeping the interfering signal from TX RB constant. Since DRM+ coverage is supposed to be larger than FM coverage, the trial's geographical area is extended as compared to the 1st field trial. The following measurement approaches shall be used to assess and compare coverage of TX FH:

P1: FM coverage shall be measured with standard procedures [5] to assess the 'nominal' or 'reference' FM coverage.

P2: FM and DRM+ coverage shall be measured with non standardized procedures relying on quality figures, e. g. SINAD, (S/N) or AQC for FM and $\mathrm{BER}, \text{MSC-FDR}$ or audio frame CRC errors (DRM+). The measured quality figures shall be compared to appropriate thresholds to decide whether or not this location is considered 'covered' or not. Furthermore, these figures shall be related to the RF parameters, e. g. the RF field strength or the in-band SNR.

P3: The coverage *difference* between FM and DRM+ shall be investigated based on the above mentioned non standard procedures, e. g. as follows: In an RX location, the TX power of TX FH is lowered up to the point that FM coverage – according to the defined quality threshold – is 'lost'. Then, the modulation is switched to DRM+. If DRM+ coverage is achieved, then DRM+

TX power is further reduced until loss of coverage. This scenario assumes that DRM$^+$ has a better coverage as compared to FM. If this is not the case, then, the DRM$^+$ TX power is increased up to the point where coverage is just 'achieved'.

Note that for P1 and P2, in order to get comparable coverage results, RX conditions shall be the same, e. g. same TX powers (TX FH, TX RB) and multipath propagation.

D. Stationary and mobile measurements

Stationary measurements shall be carried out in selected, representative locations. Coverage shall be measured using (a) a directional antenna, oriented towards TX FH in 10 m height above ground level (agl) using P1, P2 and P3, and (b) with a ND antenna in 1 m height agl with P2 and P3. In cases where DRM$^+$ coverage is marginal, cluster measurement around the RX location shall additionally be performed to decide whether or not the poor coverage is due to (a) flat fading or (b) quite simply to lack of RX power. In the latter case, this location lies on the coverage area's border.

Mobile measurements based on P2 shall be done along a predefined representative route within the trial's area. Quality and RF parameters shall be recorded along with their geographical reference in equally spaced distances respecting Lee's theorem [20].

Both measurement scenarios will *at least* take into account frequency offsets $\Delta f = [0, 100, 200]\,\mathrm{kHz}$.

IV. Outlook

The outlook sets out from the time of submitting this paper and is separated in short, medium, and long term activities. The short term work includes inter alia the following:

- finish the AWGN measurements describing DRM$^+$ performance,
- finalize measuring TX/RX characteristics, e. g. RX OIP3,
- implement an automated gain control loop for the digital receiver part to optimize decoding performance in multipath scenarios,
- carry out PR measurements for FM$\mapsto$DRM$^+$ and for DRM$^+\mapsto$DRM$^+$,
- determine DRM$^+$ performance for multipath scenarios,
- conduct the planned field trial including interpretation of all data recorded.

Based on both lab and field findings, the medium term activities include elaborating

- conclusive statements on DRM$^+$ coverage,
- proposals for planning paradigms and guidelines for DRM$^+$ including sample plannings.

Ideas for the long-term range include investigating countermeasures to flat fading effects on DRM$^+$ performance, i. e. setting up SFN or TX diversity field trials.

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