Time Averaged Power Control of a 4G or a 5G Radio Base Station for RF EMF Compliance

CHRISTER TÖRNEVIK1, (Member, IEEE), TORBJÖRN WIGREN1, (Senior Member, IEEE), SHIGUANG GUO2, AND KEN HUISMAN2
1Ericsson AB, 164 80 Stockholm, Sweden
2Ericsson Mobile Communications, Ottawa, ON K2K 2V6, Canada
Corresponding author: Christer Törnevik (christer.tornevik@ericsson.com)

ABSTRACT Currently, high gain antenna arrays are deployed in cellular radio systems to enhance wireless capacity. These advanced antenna systems increase the peak equivalent isotropic radiated powers (EIRPs), thereby potentially also increasing the size of the exclusion zones for radio frequency (RF) electromagnetic field (EMF) exposure that are applied to limit the presence of workers and the general public in the vicinity of the antennas. The exclusion zones are determined from the RF EMF exposure limits, typically expressed in terms of time-averaged incident power density values as provided by national authorities and regulatory bodies. To mitigate possible deployment challenges in some urban areas due to the overly conservative use of peak EIRP in determining exclusion zones, the possibility of basing the exclusion zone on a time averaged EIRP is discussed. To support this new approach, this paper presents an average power feedback controller that mathematically guarantees that the average power transmitted over a specified time window by a single radio base station stays below a determined value defining the exclusion zone. Such automation may be required by regulators to allow the use of time averaged quantities for RF EMF exposure assessment and exclusion zone determination. The developed average power controller uses a combination of controllers to regulate the rate of change of a momentary fractional frequency resource limit in the scheduler. This restricts the momentary total transmit power since the transmit power is proportional to the scheduled frequency resources. Simulation results, laboratory measurements and on-site measurements for a commercially available 5G MIMO transmitting base station are then reported, all of them verifying that the average power controller performs as intended. The average power control solution is applicable for any 4G or 5G base station, with or without MIMO transmission capability.

INDEX TERMS 4G (LTE), 5G (NR), AAS, antenna array, average power control, beam forming, EIRP, EMF, exposure, MIMO transmission, model predictive control, PD control, RF.

I. INTRODUCTION
When radio equipment is to be deployed, electromagnetic field (EMF) exposure regulations need to be accounted for. These regulations define limitations commonly referred to as radio frequency (RF) exposure limits. These limits are typically based on the guidelines from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1] but may take different forms in some countries and regions. The aim of the RF exposure regulations is to ensure that the human exposure to RF EMF is kept below the prescribed limits. These limits have been set with wide safety margins.

When determining the RF EMF exclusion zones for deployments of multi-input-multi-output (MIMO) transmitting 4G or 5G radios with advanced antenna systems (AASs) capable of active beam steering [2], it is important to observe that the maximum beamforming gain and equivalent isotropic radiated power (EIRP) may be significantly increased as compared to traditional antennas [3]–[6], since traditional antennas do not possess the active steering enabled by the arrays of AASs. However, the time averaged gain and EIRP are similar since these antennas steer the beams in different directions to serve different users. This means that the traditionally used methods for calculating RF EMF exclusion zones based on maximum EIRP generate overly conservative results if used for AASs [7]–[9]. The resulting
RF EMF exclusion zones may cause deployment challenges for the operator. Operators can benefit from using a more realistic exclusion zone calculation based on the time averaged EIRP instead and still strictly comply with RF exposure regulations. Since it is the total exposure of a site that is regulated, the increasing co-siting of radio base stations makes the method of the paper relevant also for 2G, 3G and 4G radio base stations without AAS [10]–[12]. The very limited exclusion zones resulting for low power small cell base stations are not likely to cause deployment problems, making the results of the present paper less relevant in such cases.

ICNIRP and other RF exposure limitations are specified in terms of time averaged quantities, such as incident power density (W/m²) or electric field strength (V/m). Such reference levels have been derived from basic restrictions expressed as Specific Absorption Rate (SAR, W/kg) values, and make the practical demonstration of compliance with RF exposure limitations easier. International standards are available that describe how to measure the RF exposure over the specified time interval, below denoted by $T$ [7], [8]. Considering time averaging as intended will in most cases lead to smaller exclusion zones, since the average power density is very often significantly smaller than the momentary maximum power density [12]. Given a distance, the power density limit can be transformed to a corresponding power limitation, for the average transmitted power. Using the maximum beam gain, the exclusion zone corresponding to the maximum EIRP of the base station can therefore be reduced to one corresponding to a selected maximum average power, computed over the time interval $T$. Due to fluctuating traffic, the momentary power can be significantly higher than this selected maximum average power during shorter times than $T$, however the transmitted average power must be guaranteed to be below the determined average power threshold at all times. The scope of the paper is therefore to design, validate and characterize means to apply the actual time-averaged power for the determination of RF EMF exclusion zones. The authors are not aware of any other previous publications addressing average feedback control that guarantee compliance with the average power threshold associated with an exclusion zone. As stated above, the one sided average power constraint makes the feedback control problem hard. Therefore, it is believed that the recursive MPC based algorithm derived in the paper constitutes significant theoretical progress. Since the

The focus of the paper is on the feedback control functionality, which must provide a 100 % guarantee that the selected average power threshold is never exceeded. This feedback control problem is highly nonlinear, primarily due to the one-sided upper constraint in terms of the selected average power threshold. The problem is relatively hard, although there are controller design methods available. The most advanced methods use a state space formulation of the nonlinear dynamics together with the selected average power threshold as a constraint, when minimizing a selected criterion function as in [13]. When applied over a selected future time horizon, this approach is typically denoted model predictive control (MPC), see e.g. [13]. Due to the randomness associated with future momentary transmit powers, stochastic control may have additional benefits [14]. These methods are however all computationally intense and non-trivial to maintain in commercial systems.

The first contribution of the paper proposes a low complexity average power feedback controller, based on a combination of proportional-differentiating (PD) control [15] and a low complexity variant of MPC. The PD controller provides smooth average power regulation during normal operating conditions such as for regular traffic, while the MPC acts as a safety net that guarantees that the selected average power threshold cannot be exceeded at any given time for any traffic type. The average power feedback controller operates on a single radio base station. In the case that base stations are co-located, a certain fraction of the power determining the exclusion zone needs to be allocated to each base station. The second contribution describes the performance of the average power controller implementation, presenting simulation results in normal operation, throughput impacts, laboratory measurements as well as on-site measurements. The simulations used measured traffic profiles proportional to the transmit power as inputs, rather than conventional system simulations. The fact that a cellular network operator (Vodafone Germany) hosted the laboratory and on-site performance validations, confirms the high practical validity of the present work. The final contribution outlines how the proposed average power control functionality can be used to provide per beam average power control. This enables further reductions of the exclusion zone and/or reduces the inevitable throughput impact that follows from the use of an average power threshold, selected below the maximum power of the radio base station.

A technical report from IEC [16] was published in 2019, which mentions average power monitoring and control as a means to apply the actual time-averaged power for the determination of RF EMF exclusion zones. The authors are not aware of any other previous publications addressing average feedback control that guarantee compliance with the average power threshold associated with an exclusion zone. As stated above, the one sided average power constraint makes the feedback control problem hard. Therefore, it is believed that the recursive MPC based algorithm derived in the paper constitutes significant theoretical progress. Since the
MPC can be implemented with recursions over the look ahead time window, the proposed method has a very low computational complexity as compared to alternative control methods, yet a 100% guarantee is obtained against overshoot of the selected average power threshold. This result holds for any profile of momentary powers in the past sliding window used to evaluate the current average transmit power of the radio base station and this is believed to be a key property for the acceptance by regulatory bodies worldwide. The described solution is commercially available for classic radios with traditional antenna systems and for MIMO transmission capable AAS equipped radio base stations. The reason why the same solution can be applied in both cases is that the average power controller acts on feedback of the transmit power before the antenna pattern forms the directional properties of the transmitted power. It therefore does not matter for the average power controller if a fixed and low gain of a traditional antenna is used or if a time varying and potentially high gain of an AAS is used. The achievable maximum antenna gain is instead accounted for when the exclusion zone is determined.

The paper is organized as follows. The needed background on RF exposure standards and regulations appears in Section II. The average power control algorithm is then described in detail in section III, followed by a description of the results of the performance evaluation and testing in section IV. The paper proceeds with a discussion in section V. Conclusions and topics for future development appear in Section VI.

\section*{II. RF EXPOSURE}

\subsection*{A. REQUIREMENTS}

When cellular radio systems are deployed, applicable RF exposure requirements for the general public and workers need to be considered. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) is the major organization specifying RF exposure limitations applicable for radio equipment including mobile phones and base stations [1]. The ICNIRP guidelines are endorsed by the World Health Organization (WHO) and the International Telecommunication Union (ITU), and have been adopted in national regulations and standards in many countries. The specified limits include substantial safety margins and provide protection for all people against established adverse health effects from short-term and long-term EMF exposure. ICNIRP has recently published updated guidelines, which are assumed to be adopted widely [17]. The new ICNIRP limits applicable in most situations for base station installations are broadly the same as those in the 1998 guidelines.

Table 1 illustrates the 1998 ICNIRP reference levels, expressed as incident power density (W/m²), applicable in the frequency range from 400 MHz to 300 GHz. These are frequency dependent up to 2 GHz and constant above. In Table 1 $f$ denotes the carrier frequency in MHz for the power density limits, and in GHz for the averaging time which is 6 minutes up to 10 GHz and then decreases with frequency. This means that the averaging time for common millimeter wave (mmW) frequency bands is 1-2 minutes. As a consequence, the average power controller is designed to operate with similar characteristics between 30 s and 30 minutes.

The power density can be measured using commercially available field strength meters, which facilitates compliance assessment processes and the determination of exclusion zones. Alternatively, computations can be used. The power density is directly related to the power (or EIRP) and the distance from the antenna. This fact is important for the average power controller presented in the paper, since it relates the RF exposure limit to a power and a distance.

\begin{table}[h]
\centering
\caption{ICNIRP power density limits (reference levels).}
\begin{tabular}{|c|c|c|}
\hline
Object & Power density & Averaging time \\
\hline
General public, 400 MHz - 2 GHz & $f/200$ W/m² & 6 minutes \\
Workers, 400 MHz - 2 GHz & $f/40$ W/m² & 6 minutes up to 10 GHz and $68/f^{1.05}$ above \\
General public, 2 - 300 GHz & 10 W/m² & 6 minutes up to 10 GHz and $68/f^{1.05}$ above \\
Workers 2 - 300 GHz & 50 W/m² & \\
\hline
\end{tabular}
\end{table}

\subsection*{B. EXCLUSION ZONES}

Traditionally, RF exposure exclusion zones have been determined based on the maximum power or EIRP of a base station. To explain the principle for an AAS equipped base station, note that the maximum EIRP is given by the product of the maximum transmit power and the maximum beam gain. It follows that the maximum power density roughly equals the maximum EIRP divided by $4\pi$ and the squared distance from the antenna, along the bore sight direction. Given the RF exposure limit expressed in terms of the power density, the RF exposure compliance distance follows. In practice the procedure is more advanced, and may involve electromagnetic field solvers based on Maxwell's equations, see e.g. [6].

The problem that motivates this paper can now be explained. Since the beam gain increases significantly when AASs are introduced, the size of the exclusion zone increases, assuming the same transmit power and that the actual time-averaged value has not been taken into account. This is challenging in particular in the case of co-siting where the combined RF exposure from all antennas need to be considered to meet the EMF limits at a site. Fig. 1 shows an example of exclusion zones for the general public (light green) and workers (red) calculated using the ICNIRP limits and the tool IXUS (Alphawave, South Africa), and for a roof-top site with a 5G AAS radio co-located with 2G, 3G and 4G antennas. The exclusion zone for the general public extends

\footnotesize

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The average power controller then forms the difference (the control error) between the reference value and the estimated radio system. The selected average power threshold associated with the exclusion zone is used to compute the average total power reference value of the control loop. The advantage to the alternative using the measurement of the total momentary power in the radio, is that the complete solution is in the base-band without radio impact, a fact that significantly simplifies testing. Later, measured power in the radio can be integrated directly if needed, but the rest of the feedback control loop is identical for both alternatives. Finally, the latest momentary power sample is stored in a sliding window of duration $T$, and the oldest momentary power sample in the sliding window is shifted out. The average power is then computed for each sampling time instance of the feedback loop.

### B. RATE CONTROLLED ACTUATOR MECHANISM

The actuator mechanism resides in the scheduler and it is selected to be a dynamic resource limit, operating on the resource grid of the OFDMA downlink air-interfaces of 4G and 5G [3], [18]. The actuator limits the maximum allowed usage of the scheduled user data resources on the Physical Downlink Shared CHannel (PDSCH) [19], [20] at any given point in time. The control data on the Physical Downlink Control CHannel (PDCCH) [19], [20] and other common channels are unaffected. This avoids any fluctuations of, for example, coverage that could result from limitations imposed on PDCCH. More precisely, the dynamic resource limit determines the maximum fraction of the physical resource blocks (PRBs) that the scheduler may use at each time instant. The range of the dynamic resource limit is thus $[\gamma_{\text{low}}, 1]$, where $\gamma_{\text{low}}$ denotes a lower limit on the maximally schedulable resources. $\gamma_{\text{low}}$ is related to the finest usable granularity when scheduling PRBs, [21], in NR. Since the threshold is to be dynamic, i.e. continuously adjusted, it is described by a differential equation with the input being the rate of change of the threshold and the output being the threshold value. This implies that the threshold value $\gamma(t)$ is determined by

$$\dot{\gamma}(t) = u(t),$$

where $t$ denotes time and where $u(t)$ denotes the control signal from the controller determined in the following subsections. A Laplace transformation gives

$$\gamma(s) = \frac{1}{s} u(s).$$

Here $1/s$ represents an integrator in the Laplace transform domain.

The above equations are linear, and there is therefore no guarantee that the range is always contained. It is hence

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About 24 meters, which can be challenging in urban areas with narrow streets. The exclusion zone may be significantly larger in countries with limits that are below the ICNIRP limits.

The relatively large exclusion zone is at least in part due to the very conservative power assumption of a maximum EIRP in all directions at all points in time, and not considering time averaging. For this reason, the international standards are introducing the concept of “the actual maximum power”, [17], for use in EMF compliance assessment.

The approach in this paper exploits the use of the actual maximum power: the average power measured over the time interval $T$. This average power is consistent with the original time averaging used to define the RF exposure limits, in terms of e.g. SAR. As shown in [12] the average power contributing to RF exposure in a massive MIMO system is very seldom higher than 25% of the maximum power. Thereby, a reduction of the exclusion zone distance to about 50% of the one corresponding to the maximum EIRP can be expected if a realistic time averaged EIRP is used. However, it is recommended in [16] that when using the actual maximum power, functionality should be available in the base station that ensures that the corresponding average power threshold is not exceeded. The average power controller described here achieves this objective.

### III. AVERAGE POWER CONTROL

#### A. ARCHITECTURE

The task to maintain the average transmit power of a single radio base station below a selected threshold associated with the exclusion zone can be formulated as a feedback control problem, as depicted in Fig. 2.

This selected threshold is denoted $\varepsilon$ below, and it is expressed as a fraction of the maximum power of the regulated radio system. The selected average power threshold associated with the exclusion zone is used to compute the average total power reference value of the control loop. The average power controller then forms the difference (the control error) between the reference value and the estimated average power. Based on this information a control signal is computed as described below. This control signal commands a rate of change to a dynamic actuator operating in the scheduler. The actuator consists of a momentary resource limitation operating on the resource grid of the OFDMA air interface [3], [18]. The scheduler then creates the data stream that is further processed in the radio to generate the transmit power. In the feedback path, two architectural alternatives are shown. The first one is the one described in the paper. This alternative performs a computation of the momentary total transmit power of the cell in base-band, after scheduling. The advantage to the alternative using the measurement of the total momentary power in the radio, is that the complete solution is in the base-band without radio impact, a fact that significantly simplifies testing. Later, measured power in the radio can be integrated directly if needed, but the rest of the feedback control loop is identical for both alternatives. Finally, the latest momentary power sample is stored in a sliding window of duration $T$, and the oldest momentary power sample in the sliding window is shifted out. The average power is then computed for each sampling time instance of the feedback loop.

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**FIGURE 1.** ICNIRP based exclusion zone for an AAS equipped 5G base station (3.5. GHz) co-located with 2G, 3G and 4G antennas. The horizontal extension is 24 m and the vertical extension is 9.6 m. Deployment may become challenging when streets are narrow.
necessary to process \( \gamma(t) \) further with the following saturation, before it may be used by the scheduler to restrict the resource allocation.

\[
\hat{\gamma}(t) = \begin{cases} 
1.0, & \gamma(t) \geq 1.0 \\
\gamma(t), & \gamma_{low} < \gamma(t) < 1.0 \\
\gamma_{low}, & \gamma(t) \leq \gamma_{low}.
\end{cases}
\] (3)

It needs to be noted that the maximum momentary power of the radio transmitter subject to the relative quantity \( \bar{\gamma}(t) \) is approximately \( \bar{\gamma}(t)P_{max} \), where \( P_{max} \) is the maximum power of the radio transmitter. This follows since digital radios are linear with respect to the scheduled fraction of the bandwidth, with great accuracy.

**C. PD CONTROL**

The average power control loop is designed to include integrating control, i.e. to compute the control signal at least partly from the integral of the control error [15]. The magnitude of the control signal will then increase whenever there is a remaining control error with constant sign. The advantage is that the actuator will act increasingly hard to remove the control error. If the dynamics is linear the only way a steady state solution can be achieved is when the integrating controller steers the control error to zero, in which case the reference value equals the measured output signal of the system. This property holds provided that the control system is asymptotically stable, irrespective of the dynamics and possible modeling errors associated with the un-controlled system [15].

On the negative side, integrating control reduces stability margins which is the reason why proportional-integrating (PI) control applies a mix of proportional and integrating control, using the dynamic controller

\[
F_y(s) = \left( C_1 + \frac{1}{T_I s} \right).
\] (4)

Here \( C_1 \) is the proportional gain and \( T_I \) the integration time, while \( F_y(s) \) is the transfer function of the controller. It can be noted that since the controller has two free tuning parameters, the proportional gain and the integration time, arbitrary pole locations can be assigned for any second order feedback loop [22].

The average power controller described here will make use of the lower realization of PI control shown in Fig. 3. That realization factors out an integrator, this integrator being the one of the dynamic actuator. As can be seen in Fig. 3, the remaining dynamics of the PI-controller resembles a proportional term and a differentiating term. The average power controller is hence a PD controller together with an integrating resource limiting threshold, together implementing integrating average power control.

![Figure 2](image-url)  
**FIGURE 2.** Block diagram of the average power feedback control loop for the alternatives with computed and measured momentary power.

![Figure 3](image-url)  
**FIGURE 3.** Two realizations of PI control, the lower one with a factored out integrator that is applied in the paper.
controller design process and it is a standard approach in the controller design field. A Laplace transformation of (6) gives the frequency domain model

\[ \langle P_{\text{tot}}(s) \rangle = \frac{1}{sT + 1} P_{\text{tot}}(s). \]  

(7)

Connecting the linear part of the components of Fig. 2, given by (2), (5) and (7), and traversing the feedback loop, gives the closed loop transfer function

\[ \langle P_{\text{tot}}(s) \rangle = \frac{P_{\max} C + P_{\max} T_D C s}{s^2 + \left( \frac{1}{T} + P_{\max} T_D C \right) s + P_{\max} C} \langle P_{\text{tot}}^{\text{ref}}(s) \rangle. \]  

(8)

To determine the two parameters of the PD controller, they are first related to desired closed loop pole locations in the complex plane using pole placement design [22]. The advantages with pole placement are that the response time of the closed loop system will be inversely proportional to the distance from the desired poles to the origin of the complex plane, and that linear stability is guaranteed provided that the desired closed loop poles are located in the left half complex plane [22]. Towards that end a closed loop denominator polynomial in \( s \) with poles in \(-\alpha_1\) and \(-\alpha_2\) is postulated as

\[ P_{\text{desired}} = s^2 + (\alpha_1 + \alpha_2)s + \alpha_1 \alpha_2. \]  

(9)

Equating coefficients between (8) and (9) and solving the resulting system of equations gives

\[ C = \frac{\alpha_1 \alpha_2}{P_{\max}}, \]  

(10)

\[ T_D = \frac{\alpha_1 + \alpha_2 - \frac{1}{T}}{\alpha_1 \alpha_2}. \]  

(11)

It can be noted that the PD controller requires an estimate of the derivative of the control error \( e(s) \). Since differentiation is sensitive to noise, the estimate of the derivative is obtained with low pass filtering as

\[ \langle \dot{e}(s) \rangle = \frac{\alpha}{s + \alpha} \left( \langle P_{\text{tot}}^{\text{ref}}(s) \rangle - \langle P_{\text{tot}}(s) \rangle \right). \]  

(12)

Here \( s \) denotes differentiation and \( \alpha \) determines the bandwidth of the low pass filter. Finally, a nonlinearity is introduced by noting that the control objective is one sided, i.e. the task is to stay below a selected average power threshold. It is therefore only relevant to have differentiating (braking) control action when the control error decreases due to an increase of the average power. This can be obtained as follows, working in the time domain

\[ u(t) = CT \langle \dot{e}(t) \rangle + CTT_D \min(0.0, \langle \dot{e}(t) \rangle). \]  

(13)

The PD controller is intended to operate when the average power is close to \( e P_{\max} \). This reflects the setting of the reference value, which is why the PD controller will have little or no effect for low average powers, regulating \( \gamma(t) \) to 1.0. Therefore, the PD controller is only activated when the average power is high enough, using the logic

\[ \text{turn on PD control} \quad \gamma(t) = 1.0 \]  

else if \( \langle P_{\text{tot}}(t) \rangle \leq \delta_1 P_{\max} \) turn off PD control

(14)

Here \( \delta_1 > \delta_2 \) are constants between 0 and 1.

D. MODEL PREDICTIVE CONTROL

As will be seen below, the average power control loop based on PD control solves the one-sided constrained average power control problem for normal traffic. However, to provide guarantees that the selected average power threshold is never exceeded, an additional algorithm is needed. This is because so far mostly linear techniques have been used, with little consideration of the one-sided selected average power threshold constraint that is a result of the selected exclusion zone.

To design the algorithm needed to provide a 100 % guarantee against average power threshold overshoot, an analysis of a theoretical power profile is presented next. This power profile is depicted in Fig. 4, and it is a worst case in the sense that it represents the quickest possible reach of the average power threshold. This analysis then leads to the relevant control problem statement. It is first noted that it is not possible to limit the momentary power to zero. The reason is that PDCCCH is untouched and that it is not desirable to regulate PDSCH all the way to zero schedulable PRBs. This situation is illustrated by Fig. 4. As can be seen, the momentary power window of duration \( T \) is first filled with zero power samples (yellow) during initialization, after which maximum momentary power is turned on. This leads to a linear increase of the average power (green). As illustrated by the lower diagram, the momentary power then needs to be reduced at some point in time, here to \( \gamma_{\text{low}} P_{\max} \) (yellow and dashed). The lower diagram shows a predicted situation ahead in time (dashed), used for the analysis performed by the model predictive control (MPC) algorithm outlined below. In the example of Fig. 4, the average power precisely hits the selected average power threshold at the end of the predictive window. The figure thus illustrates a case where an overshoot of the selected average power threshold would occur when time increases further. This follows since when the averaging window is shifted to predict further ahead, samples with zero momentary power are shifted out of the averaging window and samples with non-zero momentary power are shifted into the averaging window, resulting in a net increase of the average power. This discussion puts the focus on the problem: how to decide when regulation to \( \gamma_{\text{low}} P_{\max} \) needs to start, so that the average power always remains below the selected average power threshold (red)?

It is noted that any successful method needs to provide such a guarantee, irrespective of the power profile in the current averaging window of momentary powers.
Some consideration reveals that the control problem to solve can be formulated as:

Control problem: Given a current time \( t_0 \), a momentary power profile \( P_{tot}(t), t = t_0, \ldots, t_0 - (N - 1)T_S \), in the averaging window, and a minimum controllable power of \( aP_{max}, a \in [0.0, 1.0] \), then what is the maximum possible average power during the coming \( T \) seconds (\( N \) samples), i.e. for \( t = t_0 + T_S, \ldots, t_0 + NT_S \), provided that \( \gamma(t) = aP_{max} \) at future times?

The guarantee that the average power is never exceeded is then obtained by the following control strategy:

Model predictive control: If \( \langle P_{tot}\rangle(t_0+iT_S) > (1-\beta)P_{max} \), for some \( i \), where \( \beta > 0 \) is a small margin, then

\[
\gamma(t) = a. \tag{15}
\]

In the present paper \( a = \gamma_{low} \) is used, this is however not necessary.

To apply the MPC strategy given by (15), the future average powers need to be evaluated in an efficient way. As it turns out the most efficient way to compute the average power for future times, is to start by locating the look ahead window to predict a time ahead. In such a situation, there is no contribution from the backward window of Fig. 4. Then the window is moved one sample towards the left, leading to a recursive computation of the sought average power \( \langle P_{tot}\rangle(t_0+iT_S), i = 1, \ldots, N \).

To outline the details, it first follows that

\[
\langle P_{tot}\rangle(t_0 + IT_S) = \frac{NaP_{max}}{N} = aP_{max}. \tag{16}
\]

Then for the window positions indexed by \( N > i \geq 0 \),

\[
\langle P_{tot}\rangle(t_0 + iT_S) = \frac{iap_{max}}{N} + \frac{P_{tot}(t_0) + \cdots + P_{tot}(t_0 + (i - (N - 1))T_S)}{N}. \tag{17}
\]

Note that the contribution from the backward window contains the \( N-i \) last momentary power samples, for \( N > i \geq 0 \). This means that the sum of power contributions from the backward window of Fig. 4 can be recursively computed, by introduction of the backward accumulated power

\[
P_{\text{backward},i} = P_{\text{backward}}(t_0 + (i - (N - 1))T_S)
= P_{\text{tot}}(t_0) + \cdots + P_{\text{tot}}(t_0 + (i - (N - 1))T_S). \tag{18}
\]

This quantity can be recursively computed as follows:

\[
P_{\text{backward},N} = 0.0
i = N
while \( i > 2 \)
\begin{align*}
& a \leftarrow i - 1 \\
& P_{\text{backward},i} = P_{\text{backward},i+1} \\
& +P_{\text{tot}}(t_0 + (i - (N - 1))T_S)
end.
\end{align*} \tag{19}

Since (17) and (18) imply that

\[
\langle P_{tot}\rangle(t_0 + iT_S) = \frac{iap_{max} + P_{\text{backward},i}}{N}, \tag{20}
\]

it follows that (15), (19) and (20) together define a recursive MPC algorithm that provides a hard guarantee against exceeding \( eP_{max} \). The MPC algorithm acts as a safety net that activates control of \( \gamma(t) \) when needed, possibly overriding the PD controller.

E. DISCRETIZATION AND ACTUATOR QUANTIZATION

The actuator and the PD controller are defined in continuous time. However, the implementation is to be performed in a computer, in discrete time. This means that all dynamic parts of the controller and actuator need to be discretized. The averaging of the momentary power does not need to be discretized since this is done at sampling rate, either by a recursive computation of the true average, or by applying summation. The discretization is performed with the Euler approximation, however other alternatives like the Tustin approximation could be used as well. The Euler approximation replaces the Laplace transform variable \( s \), with the discrete time approximation of this derivative operator, i.e.

\[
s \rightarrow \frac{q_{TS} - 1}{T_S}. \tag{21}
\]

Here \( q_{TS} \) denotes the one step delay operator, running with sampling period \( T_S \). When the operator replacement is performed, the actuator given by (2) is transformed into

\[
\gamma(t + T_S) = \gamma(t) + T_Su(t). \tag{22}
\]
The PD controller (13) is transformed into
\[
u(t) = CT \left( \langle P_{\text{tot}} \rangle_{\text{ref}}(t) - \langle P_{\text{tot}} \rangle(t) \right)
- CT \left( T_D \max(\langle \dot{e} \rangle(t), 0.0) \right),
\]
where the discretized derivative of the control error obeys
\[
\langle \dot{e} \rangle(t + T_S) = (1 - \alpha T_S) \langle \dot{e} \rangle(t) + \alpha (\langle e \rangle(t + T_S) - \langle e \rangle(t)).
\]

The equation (24) assumes that the average power reference value is constant.

F. IMPLEMENTATION ASPECTS
The average power controller is implemented in the base band part of 4G or 5G base stations. The functional division follows Fig. 2 closely, thereby also preparing for any future change to a use of measured transmit power in the radio. The momentary power is summed up over all transmission time intervals (TTIs) that occur during the sampling period. This keeps the average power and the derivative updated continuously. The MPC algorithm is also running continuously since it is intended to supervise and act as a safety net, while the PD controller is activated only according to the logic of (14). The reason is that the PD controller is intended to handle normal traffic situations and not extreme average power transients.

The computational complexity is a central implementation parameter. To address the computational complexity, it is noted that the actuator, the PD controller, and the MPC controller are updated once every sampling period. A consideration of (3), (22), (23) and (24) shows that the actuator and the PD controller require of the order of 10 arithmetic operations per sampling interval. The computational complexity of the MPC controller follows from (19) and (20). Each index \(i\) requires 1 arithmetic operation, therefore (19) requires approximately \(N\) arithmetic operations and (20) requires approximately \(N\) additional arithmetic operations, per sampling interval. Since \(N \gg 10\), it follows that the actuator, the PD controller and the MPC controller together require approximately \(2N/T_S\) arithmetic operations per second. The summation of power over each TTI is more computationally intense. In case a summation over each resource element of the resource grid is performed, each physical resource block (PRB) consumes \(12 \times 14 = 168\) arithmetic operations since each PRB contains 14 symbols and 12 frequencies [19], [20]. The entire frequency band contains 100 PRBs [19], [20], resulting in 16800 arithmetic operations per TTI and time-frequency resource grid. In case the number of MIMO layers are \(L\), the computational complexity per TTI would be \(L \times 16800\) arithmetic operations, which gives the following expression for the total number of operations per second as
\[
O = \frac{2N}{T_S} + \frac{16800L}{T_{TTI}},
\]
where \(T_{TTI}\) is the duration of one TTI. A typical case with \(N = 600, T_S = 0.6\) s, \(L = 8, T_{TTI} = 0.001\) s, results in \(O = 134000000\) s\(^{-1}\). This is less than 0.1 % of the available base band processing resources, i.e. negligible.

The functionality is prepared for averaging times between 30 s and 30 minutes. This wide range is achieved by using the same averaging window containing 600 momentary power samples, while scaling the sampling period of the average power controller with the averaging time as
\[
T_S = \frac{T}{T_0} T_{S,0}.
\]
Here \(T_0\) is a nominal averaging time, e.g. 6 minutes, and \(T_{S,0}\) is the sampling period applied for the nominal averaging time. Note that the use of 600 samples is by no means necessary, other numbers can be used as well. The scaling of (26) is motivated by the Nyquist sampling theorem [23]. Since a doubled averaging window means that the bandwidth of the controlled process is halved, it follows that the sampling time can be doubled. Furthermore, since an increase of the averaging window reduces the time variation of the average power proportionally, it also follows that the controller itself can be made proportionally slower. The desired pole locations and filtering bandwidth of the derivative estimator can therefore be scaled as follows using the time constants \(\alpha_1, \alpha_2\) and \(\alpha_0\) applied for the nominal sampling period
\[
\alpha_1 = \frac{T_0}{T} \alpha_1, \quad \alpha_2 = \frac{T_0}{T} \alpha_2, \quad \alpha = \frac{T_0}{T} \alpha_0.
\]

The main configuration of the average power control system is obtained by selection of the averaging time \(T\), and the selected average power threshold \(\epsilon\) associated with the selected exclusion zone.

Operators and regulators may monitor the operation and performance by a variety of counters that provide the histograms of e.g. the momentary and average power distributions, collected with certain periodicity. This way it can be verified that no events occur that violate the selected average power threshold, associated with the selected exclusion zone. There are also counters that can be used to quantify the amount of regulation that occurs.

Finally, it is noted that the main difference between a SISO and MIMO base station implementation lies in the need to sum up the power contributions per TTI, over \(L\) layers in the MIMO case. This makes the implementation of the MIMO case more computationally intense.

IV. PERFORMANCE
A. SIMULATION
The initial performance evaluation was performed using MATLAB simulation, based on measured traffic profiles proportional to the transmit power. The traffic profiles were obtained by logging of traffic in medium to high loaded MIMO capable macro cells in a commercial 4G network.
The bandwidth was 20 MHz, and the radio propagation was urban in general. Such traffic profiles are relevant since 4G and 5G traffic mixes are very similar initially, and since average power control is most needed in high power MIMO capable base stations. The traffic profiles were sampled with a sampling period of 1 second followed by interpolation to the sampling period used for evaluation. This enabled a quick development, based on realistic input signals. The reason why link and system simulations were avoided is the time constant of 6 minutes, which implies simulation times of several hours to compute a single realization of the feedback control performance. The associated computational volume would therefore become far too high if link and system simulations were used for development and tuning of all parameters. The parameters of the simulator appear in Table 2. Since the average power controller was fielded recently, live traffic data with intensity high enough to trigger the average power controller in NR networks is not yet available. Therefore simulations using a bit-exact replica of the product code is used to illustrate performance in this paper.

**TABLE 2. Average power control software parameters.**

| Parameter | Description                                      | Value         |
|-----------|--------------------------------------------------|---------------|
| $P_{max}$ | Maximum transmit power                           | 200 W         |
| $\varepsilon P_{max}$ | Average power threshold                        | 50 W          |
| $T$       | Averaging time                                   | 360 s         |
| $\gamma_{low}$ | Minimum actuator value                         | 0.15          |
| $\delta_1 P_{max}$ | PD control activation level               | 43.5 W        |
| $\delta_2 P_{max}$ | PD control de-activation level               | 34 W          |
| $(P_{tot})_{ref}$ | PD control reference value                  | 43 W          |
| $T_0$     | Nominal averaging time                          | 360 s         |
| $T_{S,0}$ | Nominal sampling period                         | 0.60 s        |
| $\alpha_{1,0}$ | First nominal closed loop pole                 | 0.0167 s$^{-1}$ |
| $\alpha_{2,0}$ | Second nominal closed loop pole                | 0.0300 s$^{-1}$ |
| $\alpha_0$ | Nominal differentiation pole                    | 0.0750 s$^{-1}$ |
| $\alpha P_{max}$ | Minimal MPC power level                    | 30 W          |
| $\beta P_{max}$ | MPC power margin                                | 4 W           |

Simulation results for normal to high traffic are depicted in Fig. 5 and Fig. 6. As can be seen in Fig. 5, the actuator provides a mix of smoothly varying PD control and fast regulation to minimum actuator level when the MPC algorithm is needed to ensure that the average power remains below the threshold associated with the exclusion zone.

The setting of the average power threshold to 50 W, i.e. to 25 % of the maximum transmit power, leads to an exclusion zone with dimensions that are roughly 50 % of those obtained for 200 W. This follows since the power density in the far field region is inversely proportional to the square of the distance to the antenna.

The average power controller obviously reduces the cell throughput, which is why it is highly relevant to assess the throughput reduction. In this paper this is done with simulation. Since reference [12] shows that the average power in a high end 4G MIMO capable base station is very seldom above 25 % of the peak power, the average power setting of the power profiles used in Fig. 5 were retained when evaluating the throughput loss. As compared to Fig. 5 the simulation time was however extended to 24 hours. The simulation was repeated for different values of the average power threshold $\varepsilon P_{max}$. The PD-control activation level, PD-control de-activation level, PD-control reference value and the MPC power margin were all scaled accordingly, using the scale factor $\varepsilon / 0.25$. The throughput loss was then recorded as a function of the threshold parameter $\varepsilon$, with the result depicted in Fig. 7. In this case it can be seen that throughput loss is close to 10 % for $\varepsilon = 0.25$, and that it is quickly reduced with increased threshold values, becoming less than 1 % when the average power threshold is around 0.37. This value is dependent on the traffic profile and the load, however the results clearly show the effectiveness of the actual maximum power. Note also that the throughput loss for $\varepsilon = 0.25$ is consistent with a visual inspection of Fig. 6.
and with an averaging time of 6 minutes ($\varepsilon = 3.1$ m). The power control feature was set to control the distance between the base station and the field strength probe immediately increased to a stable level of 2.2 W/m$^2$. This is below 0.84 W/m$^2$, which corresponds to 25 % of the power density at peak power ($(0.25/0.65) \cdot 2.2$ W/m$^2 = 0.84$ W/m$^2$).

C. ON-SITE TESTS

In addition to the laboratory tests, measurements were also conducted to validate the functionality of the average power controller on a 5G site in a live mobile network, by showing that the time-averaged power is controlled below the set threshold, never exceeds it, and that the corresponding RF EMF exposure is maintained below the configured threshold as intended. Note that the tests were limited to validation of the average power controller. They were not intended to illustrate performance in a normally loaded network.

The measurements were conducted in one of the sectors of a three-sector 5G site installed on a parking garage in the Vodafone network in Düsseldorf, Germany. Fig. 9 shows a photograph of the site. The 5G base station, installed 11.8 m above the garage floor, was an Ericsson AIR 6488 (NR, TDD) operating in the B78F (3542 MHz - 3700 MHz) frequency band. The peak power was 80 W, the bandwidth 40 MHz and the downlink transmission duty cycle 74.5 %. Codebook-based beamforming (32-port CSI-RS) was applied resulting in a maximum gain around 24 dBi in the boresight direction of the 64-port antenna array. The azimuth and elevation angles to the measurement point, located 32 m from the 5G antenna, were about 7 and 17 degrees off boresight, respectively. In this direction the antenna gain of the beam used to provide data was approximately 16 dBi.

To be able to measure the 5G signal accurately and ensure that contributions from other RF sources were not included, a frequency selective electric field strength meter (Narda SRM-3006) with an isotropic probe was used. It was remotely controlled by a laptop PC and set to measure the root mean square (RMS) of the signal. The power density measurements were taken using a resolution bandwidth of 20 MHz and an averaging time of 0.48 s. Since the maximum resolution bandwidth was limited to 32 MHz, sequential 20 MHz measurements were made to capture the 40 MHz bandwidth of the 5G signal. Like for the laboratory measurements, a UE (Qualcomm) and the iPerf tool were used to control the data transmission from the base station. The UE was placed about 3 m behind the EMF probe, which ensured an insignificant contribution from the uplink signal and that the measurements were taken within the beam serving the UE.

Both instantaneous and 6-minute time-averaged power density data were acquired and stored. To minimize the impact of multi-path fading, a large area of the parking space...
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FIGURE 8. Measured instantaneous (red) and time-averaged (black) power density with the power control feature inactive and active. The power on and average power control activation times are indicated with arrows. The green dashed line represents 0.84 W/m$^2$ which corresponds to 25 % of the power density at peak power, and the dashed black line represents 0.78 W/m$^2$ which is the maximum time-averaged power density measured with the power control feature activated. The test was conducted in a shielded 5G test chamber using a broadband EMF meter.

was closed, and persons were not allowed to get close to the EMF probe and the UE during the measurements. The measurement setup was thus selected to achieve transmission dominated by LOS propagation, thereby avoiding multi-path and frequency selective fading to allow comparison with the laboratory tests. A number of test cases with different traffic loads and patterns were investigated with the power controller active and with the averaging time set to 6 minutes and the average power threshold set to 25 % of the peak power. Before each test a baseline measurement was conducted with the power controller inactive and at the maximum output power to get power density values for normalization of measurement data when the power controller was activated.

Fig. 10 shows the results of the power density measurements for the test case with maximum data throughput (“full buffer”), maximum transmit power, and with the average power control activated. The red curve shows the instantaneous power density values and the black curve the 6-minute average values. The blue dashed curve indicates the baseline reference value (0.13 W/m$^2$) corresponding to peak power (80 W) transmission and the green curve indicates the 25 % level corresponding to 20 W power. As can be seen, the time-averaged power density never exceeds the 25 % level that was set. The maximum value was 0.033 W/m$^2$ which corresponds to 22 % of the EMF exposure for maximum power. For the other test cases, with different traffic loads, the measured time-averaged power density was also below the set 25 % power level.

The time-averaged power was also monitored during the tests using available counters and the results showed that not a single measurement sample was above the set threshold of 25 % of the peak power.

V. DISCUSSION

A. AVERAGE POWER LEVELS CLOSE TO THE THRESHOLD

When the average power level increases to levels close to the threshold, the MPC part of the algorithm becomes dominating. As can be seen in the on-site test measurements, the controller then begins operation in a switching mode. This is expected and can be explained as follows, having Fig. 4 in mind.

Assume that maximum momentary transmit power is required to meet the incoming traffic when the average power control function starts and that the parameters of Table 1 are used. Without average power control, the average power threshold would therefore be exceeded already after 90 s. Therefore, the MPC safety net reduces the actuator level to the minimum value, well before 90 s. The averaging window then begins to shift in minimum momentary power samples. This continues until the MPC algorithm concludes that there is no risk that the average power threshold will be exceeded in the coming 360 s. At that point in time, the actuator level is increased to 1.0 (unless PD control is activated), and maximum momentary power samples begin to be shifted into the averaging window, leading to a repetition of the previous cycle. The average power control problem is thus naturally
solved by a limit cycle when the average power level is approaching the power threshold. It is stressed that this is very unlikely to occur in practice, unless cells are very loaded. The explanation here is however necessary, to fully understand the operation in e.g. laboratory tests, where designed test signals are commonly used. To reduce and or completely avoid oscillation, the quantity $\gamma_{\text{low}}$ could be made configurable, to allow tradeoffs between capacity and oscillation.

### B. COMPARISON AND FEEDBACK CONTROL ENHANCEMENTS

Since the IEC technical report [16] was published quite recently, the authors are not aware of any previous academic publications on average power control for exclusion zone reduction. Some comments on the present algorithm, and possible enhancements may however be given. First, it is noted that the main theoretical development of the paper, the MPC algorithm, is a necessary part of any average power feedback control algorithm intended to solve the problem at hand. This became evident in the laboratory tests reported in Section IV.B, where the set average power threshold was repeatedly exceeded when full buffer tests were run with MPC turned off.

As can be seen in Fig. 8, an oscillation with small amplitude can occur close to the average power threshold. The theoretical explanation for this appears in Section V.A, and it is a consequence of the choice of an MPC algorithm that has a sufficiently low computational complexity. More advanced algorithms are available, at the price of an increased computational volume, see e.g. [13]. One can conjecture that the best approach to avoid oscillation and achieve efficient control would be to define an optimal control problem [13] that penalizes both control and output signals. The constraints would then be a state space version of the open loop dynamics defined by (1), (3) and (6), together with a one sided constraint expressing the fact that the average power state should always be less than the average power threshold set by the operator.

### C. DIRECTIONAL AVERAGE POWER CONTROL

The average power controller described in the paper operates per sector (or per cell). The exclusion zone reductions are obtained from the time averaging gain, as compared to the traditional exclusion zone design based on the maximum momentary EIRP.

A reduction of the possible throughput impact of the average power controller can be obtained by exploiting the directional properties of the AASs. The observation behind this fact is that the UEs served by the radio base station are spatially distributed, hence also the transmit power will be spatially distributed. The consequence is that the average power is highly likely to be significantly smaller in each separate direction, than for the whole cell. Therefore, by controlling the average power in each direction, at least parts of the throughput reduction can be avoided.

The proposed average power controller is directly applicable to the directional average power control problem. A beam gain computation on a directional grid, mapping the angular range of the AAS, can then be used to compute a normalized momentary power per beam direction bin, where the quotient of the momentary and maximum beam gains multiplied by the transmit power, provides the normalization. The momentary normalized power can then be aggregated to a normalized average power per beam direction. The procedure can be defined for codebook based as well as for reciprocity assisted transmission. The average power controller can be re-used in at least two ways. Either one instance of the feedback controller is used for each bin of the grid, or the highest normalized average power over the grid is used to provide cell wide average power control. Initial simulations show that the performance of the last method may be superior.

### D. PERFORMANCE AND THROUGHPUT IMPACT

The simulations, laboratory measurements and on-site tests all show that the average power controller achieves the objective to keep the average power below the operator selected threshold, for realistic traffic, at all times. As shown by Fig. 5, the amount of blocked traffic (blue power below the red limitation) is relatively low in cells with normal to high load and a power threshold set to 25% of the peak power. This is believed to be the situation in the majority of the 5G cells.
until the number of users increase significantly. 4G cells may however already be highly loaded.

Throughput loss in cells with high load is an inevitable consequence when exclusion zones need to be reduced by application of the actual maximum power. This is illustrated by Fig. 7 which plots the throughput loss as a function of the average power threshold parameter $\varepsilon$. An increase of the load, i.e. the average power, has a similar effect as a reduced $\varepsilon$. It needs to be stressed that in most markets, regulatory RF EMF limitations normally override requirements on throughput. To handle situations where exclusion zone reduction by means of average power control affects cell throughput significantly, the directional average power control functionality outlined in section V.B may be used for further mitigation.

VI. CONCLUSION
The paper proposed an average power control method that enables the use of actual maximum power instead of momentary maximum power when determining the exclusion zones of radio base stations. The resulting reduced size of the exclusion zones help mitigate possible deployment problems for high gain AAS equipped radio base stations, in both 4G and in 5G. The proposed method exploits the time averaging gain observed in [12], together with the fact that RF exposure regulations are defined using time averaged quantities.

The proposed controller has a unique and very important property, in that the average power threshold associated with the determined exclusion zone can never be exceeded when the average power controller is in operation. Such a hard guarantee is instrumental in achieving acceptance from regulators. The performance of the proposed controller was illustrated with simulations for normal traffic. Laboratory experiments and the result of on-site tests were also reported, giving evidence that the controller provides the claimed performance.

Topics for further work and research includes detailed development and test of a suitable directional average power control algorithm that enhances performance. In addition, more advanced controllers could be studied, also with the purpose of providing better performance and more smooth control in highly loaded cells. The one-sided constraint could perhaps be optimally handled by convex optimization in combination with optimal control and general MPC [13], [24]. A stability analysis that at minimum covers the PD control part would also be valuable. Due to the actuator limitation, nonlinear methods like the Popov criterion or the circle criterion [25], [26] could then prove useful. Inclusion also of the asymmetric differentiation term would probably require Lyapunov based methods of analysis [25]. The proposed average power controller is designed for a single radio base station, hence coordination between co-sited radio base stations is also left as a topic for future research.

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CHRISTER TÖRNEVIK (Member, IEEE) received the M.Sc. degree in engineering physics and the Ph.D. degree in automatic control from Uppsala University, Uppsala, Sweden, in 1985 and 1990, respectively.

From 2000 to 2018, he was an Adjunct Professor of automatic control with Uppsala University. Previous positions include CelsiusTech Systems AB, Stockholm, Sweden, and Bofors Aerotronics AB, Stockholm, where he was working on automotive radar, sensor data fusion for air target tracking, and fire control systems. He is currently employed with Ericsson AB, Stockholm, where he is working on signal processing and automatic control for 4G and 5G wireless systems. His research interest includes nonlinear dynamic systems. He received the Ericsson Inventor of the Year award in 2007, and the Ericsson Impact Award for 2018.

SHIGUANG GUO received the M.Sc. degree in engineering thermo-physics from Tsinghua University, Beijing, China, in 1996, the M.Sc. degree in mechanical engineering from Clarkson University, Potsdam, NY, USA, in 1999, and the M.Sc. degree in electrical engineering from Drexel University, Philadelphia, PA, USA, in 2000.

After graduation, he joined the Optical Network Division, Nortel Network, Ottawa, ON, Canada, as a DSP and a Control System Engineer. At Nortel, he worked on optical amplifiers, WIMAX, and LTE development. In 2009, he joined Blackberry, Ottawa, as a Researcher working on LTE advanced research and 3GPP standardization. In 2011, he joined Ericsson Canada, Ottawa, as a Software Engineer. He is currently working as a System Engineer with the 4G/5G Research and Development team.

KEN HUISMAN received the B.Sc. degree in computing science from the University of Alberta, Edmonton, AB, Canada, in 1992.

After working in the information technology and consulting fields for several years, he joined Nortel in 2000, and then Ericsson in 2010. There, he has been involved in software development for routers, WIMAX, radio, and indoor radio products, in development and leadership capacities. His current role is as a Product Owner (operational) for baseband 5G development. He led the team that implemented, tested, and deployed the functionality described in the present article.

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