Self-Optimization of RACH Power Considering Multi-cell Outage in 3GPP LTE Systems

*Wonbo Lee, *Dongmyoung Kim, †Seunghyun Choi, ‡Kyung-Joon Park, *Sunghyun Choi, and §Ki-Young Han
*School of Electrical Engineering and INMC, Seoul National University, Korea
†Department of Electrical Engineering and Computer Science, University of Michigan, USA
‡Department of Information and Communication Engineering, DGIST, Korea
§System Lab., Next Generation System Team, Samsung Electronics, Korea
Email:{wblee, dmkim}@mwnl.snu.ac.kr, shkchoi@umich.edu, kjp@dgist.ac.kr, schoi@snu.ac.kr, kiyoung.han@samsung.com

***Abstract*—Self-organizing network (SON), which is an essential technology of future radio networks, is proposed in the 3GPP Long Term Evolution (LTE) specification as a usage case. In this paper, we focus on user equipment (UE)'s power control considering interference mitigation and retransmission constraints especially for physical random access channel (PRACH) of LTE. When a UE initially accesses an evolved-NodeB (eNB), it sends a preamble with an initial access level, and raises the power by a fixed step whenever the preamble was not detected by the eNB. We present an analysis and simulation to study the tradeoff relationship between inter-cell interference and retransmission according to the PRACH power setting, i.e., the initial target received power and power ramping step, assuming Rayleigh fading channels. Furthermore, we propose an algorithm tracing the optimal power setting that minimizes the resource wastage of the cell in consideration and its adjacent cells satisfying the constraint of retransmission and failure probability bound.**

I. INTRODUCTION

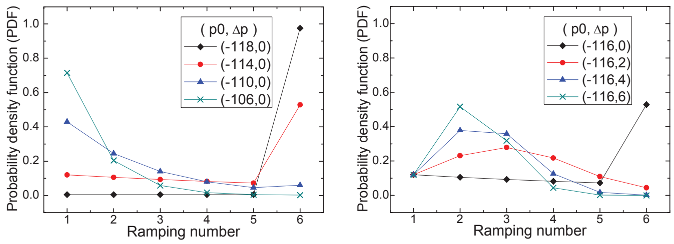
Self-Organizing Network (SON) technology enables network systems to automatically catch environmental changes and to adaptively optimize parameters for resource management. Self-configuration, self-optimization and self-healing are key techniques for SON, and they can reduce capital expenditures (CAPEX) and operational expenditures (OPEX) [1]. 3GPP Long Term Evolution (LTE), which is one of leading technologies for the next generation (4G) cellular systems, released use cases and solutions for self-configuring and self-optimizing networks [9]. It describes various scenarios that need functional configuration and optimization, and defines input/output parameters to achieve expected results.

Physical random access channel (PRACH) optimization is one of the main components for the LTE SON. Random access is required for a UE to have a new connection or reconnection with a eNB in the case of link failure, uplink synchronization request, scheduling request or handover triggering. For the random access, a UE transmits a preamble code with a certain amount of signal power on the predetermined PRACH subframe, where a frame (10 ms) includes a number of PRACH subframes (1 ms). The preamble code is chosen among a predefined number of code sequences (e.g., 64 orthogonal Zadoff-Chu sequences) [11].

On the other hand, the initial transmission power of a preamble is set to the consistent level of the initial target received power (ITRP), $p_{0,prach}$, announced by an eNB which the UE wants to associate with. This is based on the estimation of reference signal strength and full compensation for the path loss, which ensures that the received signal power of a preamble is independent of the path loss [11]. The UE can retransmit the preamble with increased power by ramping step, Δp, again if no random access response for the preamble is received within the random access (RA) response window. This is so-called power ramping scheme and repeats until the preamble is detected or the retransmission number meets the maximum number of retransmissions. The setting of PRACH power, ($p_{0,prach}$, Δp), has an effect on the probability of preamble detection. Meanwhile, a random access signal acts as an interference to other cells. The higher the transmission power is, the more interference to other cells it causes while the higher the preamble detection probability is.

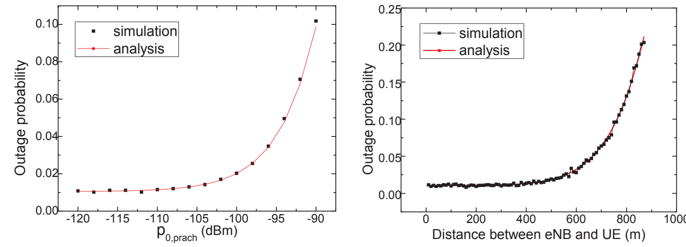
Several works for the analysis of random access delay due to the PRACH code collision and power ramping have been presented [3, 4]. Furthermore, the optimization works of PRACH to maximize the uplink capacity [6] or to minimize random access delay [3, 5] have been proposed. Recently, the research on the self-optimization of PRACH according to the change of traffic load has been reported [7]. However, the previous works do not consider the other-cell interference caused by random access signal.

In this paper, we focus on the optimization of the PRACH power setting considering both of the preamble detection probability and adjacent cell's uplink outage in Rayleigh fading environments. In [2], the authors define the outage probability as the fraction of time that a signal to interference plus noise ratio (SINR) is lower than a certain SINR threshold due to fading. They formulate the outage probability in Rayleigh fading channel and analyze its upper and lower bounds. Based on this analysis of the outage probability, we formulate an optimization problem that minimizes the maximum resource wastage caused by the preamble detection miss and adjacent cell's uplink outage. The optimization problem is non-convex because the input variables such as the PRACH power set is the integer value in decibel units. However, the objective function to minimize the expected number of adjacent cells' uplink outages and the expected number of power rampings in the problem are presented by closed-form expressions, and hence the optimal value is easily found by exhaustive search



(a) effect of $p_{0,prach}$ (b) effect of Δp

Fig. 1: Effects of the ITRP and the ramping step.



(a) effect of distance (b) effect of $p_{0,prach}$

Fig. 2: Outage effect on PUSCH.

with given parameters. The number of possible PRACH power settings is only 64 because of 16 values of $p_{0,prach}$ and 4 values of Δp; therefore, the computation overhead is low.

The next step for the PRACH power optimization is to catch the change of the random access environment such as interference and adaptively to update the power setting to the optimal value. Interference on a cell changes according to the cell load of its adjacent cells, and it directly influences the outage probability of the uplink data or the preamble detection probability of the random access. In this paper, we assume that each eNB measures time-varying interference and shares the average interference over thermal noise (IoT) value on the dB scale with its neighbor eNBs periodically, and propose the IoT-based self-optimization process of PRACH power setting.

The rest of the paper is organized as follows. The system model considered in this paper is described in Section II. In Section III, we formulate and analyze the PRACH power optimization problem. Section IV presents the IoT-based self-optimization process for the adaptive PRACH power setting and the simulation-based performance evaluation. Then, the paper concludes in Section V.

II. System Model

A. Preamble Detection Miss Model

We assume that an eNB successfully detects a PRACH preamble when the SINR at the eNB side exceeds an SINR threshold, γ^{th}_{prach}. Even though the UE transmits a signal with the same power, the received signal strength would vary because of the fast fading effect and might not be detected by the eNB at times. The UE can retransmit the preamble with increased signal strength by the predetermined step size. We consider Rayleigh fading with the additive white Gaussian noise (AWGN) in the radio signal propagation environment. Then, the detection miss probability at the k-th (re)transmission, after $(k-1)$ transmission failures, is expressed as follows [8]:

$$\begin{aligned} P^{(k)}_{miss} &= P\big(\gamma^{(k)}_{prach} < \gamma^{th}_{prach}\big) \\ &= 1-\exp\left(-\frac{\gamma^{th}_{prach}}{p^{(k)}_{prach}/N_0}\right)\cdot\prod_{j\in N_{adj}}\frac{1}{1+\frac{\gamma^{th}_{prach}}{p^{(k)}_{prach}/I_j}} \end{aligned} \tag{1}$$

where γ is the measured SINR at the eNB, $p^{(k)}_{prach}$ is the target received power of the preamble at the k-th (re)transmission, N_{adj} is the number of adjacent cells, I_j is the interference from adjacent cell j, and N_0 is the noise spectral density. Therefore, $P^{(k)}_{miss}$ is a function of the preamble power, and it directly decides preamble capturing delay. On the other hand, $p^{(k)}_{prach}$ is determined by the sum of ITRP and power ramping step, i.e., $p_{0,prach}+k\Delta p$, on the dB scale. At first, a UE transmits a preamble with $p_{0,prach}+PL$ where PL is the estimated path loss at the UE, and it would retransmit the preamble with increased power by $k\Delta p$ at the k-th (re)transmission if all the previous preambles have not been captured by the eNB. The average number of retransmissions, $\overline{N}_R(\mathcal{P})$ is represented by the detection miss probability, P_{miss}:

$$\begin{aligned} \overline{N}_R(\mathcal{P}) = &\sum_{k=1}^{N_{max}-1}\left[(k-1)(1-P^{(k)}_{miss})\prod_{i=1}^{k-1}P^{(i)}_{miss}\right] \\ &+(N_{max}-1)\prod_{i=1}^{N_{max}-1}P^{(i)}_{miss} \end{aligned} \tag{2}$$

where N_{max} is the maximum allowed number of preamble (re)transmissions, which is informed by the eNB. The last attempt imposes both the success and failure of detection because the preamble transmission would stop at the maximum retransmission number regardless of the result. An example of the probability density function (PDF) of the ramping number for a successful preamble detection according to the PRACH power setting is depicted in Fig. 1. From the figure, we can see how the ITRP and the ramping step affect preamble detecting delay.

B. PRACH Interference Model

We assume that PRACH subframes in a cell are managed not to overlap with adjacent cells. Hence, PRACH causes interference with other cell's uplink data channel, referred to as physical uplink shared channel (PUSCH), and vice versa. When a UE location in cell i is denoted by $\vec{l}$, the PRACH interference with the PUSCH in cell j can be expressed as $I_{j\vec{l}} = p^{(k)}_{prach}\cdot G_{j\vec{l}}/G_{i\vec{l}}$ where $G_{j\vec{l}}$ and $G_{i\vec{l}}$ are channel gains from location $\vec{l}$ to cell j and i respectively. Meanwhile, we adopt an outage concept in order to see more practical effect of the interference. Similarly to the preamble detection miss probability, an outage of PUSCH occurs when the uplink SINR does not exceed SINR threshold γ^{th}_{pusch}. Fig. 2 shows simulation results for the outage effect of the random access signal on adjacent cell's uplink channel according to (a) the distance from serving eNB to random access UE and (b) the ITRP for cell-edge UE. As the figure depicts, the increase of the ITRP and the distance from serving eNB make the outage exponentially increase. Accordingly, the parameter setting of the PRACH preamble power is critical to prevent severe outages of the adjacent cell's uplink channel.

III. Problem Statement and Analysis

A. Optimization Problem of PRACH Power Setting

The LTE specification defines a set of possible $p_{0,prach}$ values as $[-120 \sim -90]$ dBm with the step of the multiple of 2 dB [10]. Each UE controls its transmission power of the preamble considering the estimated path loss and detection probability. If the preamble is not correctly detected by the eNB, it is retransmitted with the same or increased power, and the ramping step Δp can be chosen among [0,2,4,6] dB [10]. The increase of a preamble power surely improves the detection probability, while it can cause more interference with other cells' uplink channel; furthermore, it would be the waste of battery energy of UEs if the transmission power is higher than the required level. Therefore, PRACH parameters for the transmission power should be properly chosen to achieve the requirement of the number of preamble retransmissions with the minimum resource wastage.

The resource wastage is regarded as the sum of PRACH resource blocks that are used for uncaptured preambles and the number of adjacent cells' resource blocks that occur outage during the random access procedure. We formulate this problem as a simple optimization problem. The objective function of the problem is to minimize the maximum expected resource wastage, $\overline{W}_{\vec{l}}(\mathcal{P})$ from the PRACH preamble retransmissions and the adjacent cells' uplink outages, where the constraints are the average number of retransmissions and the detection failure probability of the preamble. Assuming the full compensation of PRACH transmission power, the maximum number of outages of adjacent cells surely arises when the random access UE is located at the cell edge side, i.e., the vertex esof the hexagonal cell.

The optimization problem is formulated as follows:

$$\begin{aligned} \min_{\mathcal{P}} \ \max_{\vec{l}} \ & \overline{W}_{\vec{l}}(\mathcal{P}) \Big(= \sum_{j} \overline{F}_{j\vec{l}}(\mathcal{P}, IoT_j) + \omega \cdot \overline{N}_R(\mathcal{P}) \Big) \\ s.t. \quad & P_F(\mathcal{P}) \leq P_F^{cstr} \\ & \overline{N}_R(\mathcal{P}) \leq \overline{N}_R^{cstr} \end{aligned} \tag{3}$$

where $\overline{F}_{j\vec{l}}$ is cell j's expected number of PUSCH outages at the same resource blocks as random access UE's at $\vec{l}$, and IoT_j is the IoT value of the adjacent cell j. P_F^{cstr} and $\overline{N}_R^{cstr}$ are constraints of the failure probability and the average ramping number respectively. $\overline{N}_R(\mathcal{P})$ is the expected number of preamble retransmissions. ω is a weight factor for the wastage of the PRACH retransmissions, which can be tuned according to the relative significance. In this paper, we assume the weight equals one. For $\max_{\vec{l}} \overline{W}_{\vec{l}}(\mathcal{P})$, we test all of the six vertexes of the hexagonal cell and find the vertex that achieves the maximum value. Adjacent cell's uplink outage $\overline{F}_{j\vec{l}}$ is a function of $p_{0,prach}$, Δp and IoT_j, and is formulated as follows:

$$\begin{aligned} \overline{F}_{j\vec{l}} = & \sum_{r=1}^{N_{max}-1} \Big\{ P_S^{(r)} \Big(\sum_{k=1}^{r} O_{j\vec{l}}^{(k)} + (N_{max} - r) \cdot O_{j_{N_0}} \Big) \Big\} \\ & + \Big(1 - \sum_{r=1}^{N_{max}-1} P_S^{(r)} \Big) \sum_{k=1}^{N_{max}} O_{j\vec{l}}^{(k)} \end{aligned} \tag{4}$$

The observation range to count outages is N_{max} PRACH subframes for all the power settings to be compared. If the preamble with high power is early detected before N_{max}, it has influence on the adjacent cell's outage with strong interference for a short time, and the remaining subframes among N_{max} PRACH subframes has no PRACH interference; while all the PRACH subframes can interfere with adjacent cells even though its influence is relatively weak if the preamble power is low and never detected until N_{max} retransmissions. The exact meaning of the adjacent cell's outage number $\overline{F}_{j\vec{l}}$ is the average number of outage subframes on PUSCH of adjacent cell j by the random access UE with the existence of IoT_j during the predefined maximum number of retransmissions, N_{max}.

The first term of the equation represents the expected number of adjacent cells' outages that PRACH preambles cause when the preamble is successfully detected before the maximum number of retransmissions. $O_{j\vec{l}}^{(k)}$ is the outage probability at cell j with the k-th preamble (re)transmission, and is given by the formula similar to (1). This can be replaced by an alternative form using the IoT_j value, which is discussed in the next subsection. $(N_{max}-r) \cdot O_{j_{N_0}}$ is the expected outage number without the PRACH interference because the preamble was detected before N_{max}. The second term is the expected number of adjacent cells' outages when $(N_{max}-1)$ preamble transmissions have failed.

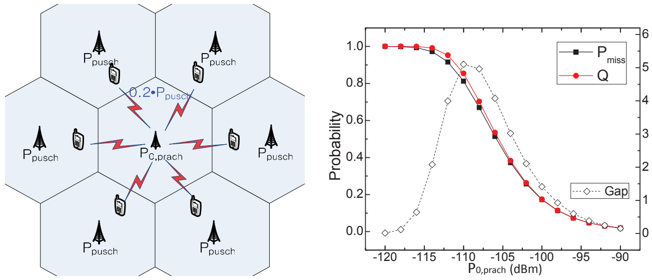
P_F is the probability that a random access preamble fails to be detected even at the maximum retransmission number, and is represented as a function of the detection miss probability:

$$\begin{aligned} P_F &= 1 - \sum_{r=1}^{N_{max}} P_S^{(r)} \\ P_S^{(r)} &= \big(1 - P_{miss}^{(r)}\big) \cdot \prod_{k=1}^{r-1} P_{miss}^{(k)} \end{aligned} \tag{5}$$

where $P_S^{(r)}$ is the probability of a successful preamble detection at the r-th (re)transmission.

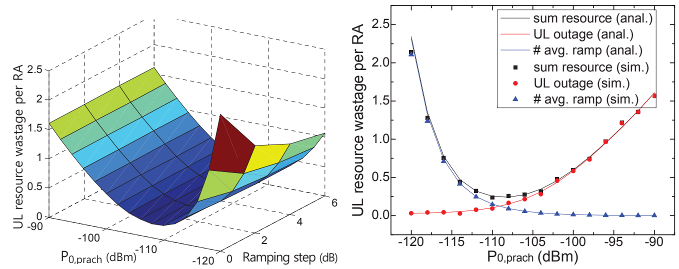
B. Conservative Approximation

In LTE systems, an eNB cannot measure the individual interference from other cells, but estimate the interference over thermal noise (IoT), which is the sum of all the interferences from adjacent cells. Therefore, it is more practical that the eNB



(a) Interference setting (b) Approximation gap

Fig. 3: Approximation gap of detection miss probability.



(a) $(p_{0,prach}, \Delta p)$ vs. UL wastage (b) ITRP vs. UL wastage

Fig. 4: Effect of PRACH power on uplink wastage.

utilizes IoT than trying to extractly measure every interference individually when controlling PRACH parameters. In [2], Kandukuri and Boyd derive a tight upper bound of the outage probability in Rayleigh fading environments. The upper bound forms an exponential function of sum interference instead of the product form of the individual interference as (1); hence the IoT can be applied into the upper bound formula, and we have

$$P_{miss}^{(k)} \le Q^{(k)} = 1 - \exp\left(-\frac{\gamma_{prach}^{th}}{p_{prach}^{(k)}/(N_0 \cdot IoT_{prach})}\right) \quad (6)$$

We evaluate the validity of this upper bound through a simulation in a topology shown in Fig. 3-(a). Random accesses occur at the center cell in the figure with ITRP of $p_{0,prach}$, and other six adjacent cells' PUSCHs are fully loaded with target received power p_{pusch}. When the location of uplink UEs in a cell is uniformly distributed, and uplink power is controlled with full compensation factor, we can derive the average interference power, $\sigma \cdot p_{pusch}$ at the adjacent cell's eNB. σ is obtained by the simulation as 0.2. We put $0.2p_{pusch}$ into each I_j in (1) and $0.2p_{pusch} \times 6$ into IoT_{prach} in (6). Fig. 3-(b) depicts the gap between (1) and (6) for all the ITRP parameters. The dashed line shows the percentage of the gap for each ITRP. We observe that the approximation gap is under 6% from the figure; therefore, the conservative approximation utilizing the IoT for the outage probability is practically applicable.

Similarly to this procedure, we obtain the conservative approximation of the outage rate $O'_{j\vec{l}}$ in (4) as follows:

$$\begin{aligned} O_{j\vec{l}}^{(k)} \le& O_{j\vec{l}}^{'(k)} \\ =& 1 - \exp\left(-\frac{\gamma_{pusch}^{th}}{p_{pusch}/(N_0 \cdot IoT'_j)}\right) \cdot \frac{1}{1 + \frac{\gamma_{pusch}^{th}}{p_{pusch}/I_{j\vec{l}}}} \end{aligned} \quad (7)$$

where IoT'_j is the approximate interference over thermal noise on cell j's uplink channel without PRACH interference of the cell in consideration. Because IoT_j includes the PRACH interference with the previous power setting, p_{prach}^{old}, IoT'_j can be expressed as $IoT_j - \sigma \cdot p_{prach}^{old}$ where $\sigma = 0.2$ if the uniform distribution is assumed.

From the mathematical analysis with conservative approximation, we plot the uplink resource wastage, $\max_{\vec{l}} \overline{W}_{\vec{l}}(\mathcal{P})$ according to the PRACH power setting, $(p_{0,prach}, \Delta p)$. We assume the worst case that random accesses occur at the vertex of the hexagonal cell. Fig. 4-(a) depicts the numerical analysis of the uplink wastage with different PRACH power setting defined in the LTE standard. Fig. 4-(b) shows the gap between analysis and simulation.

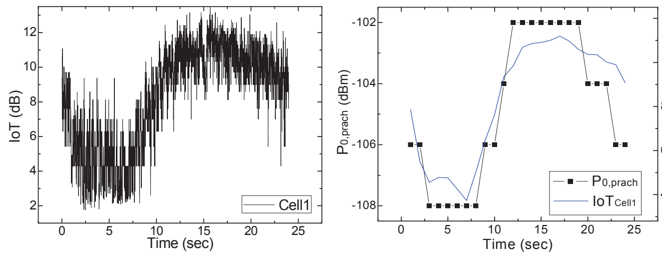
We implement a simulation with the same environment as the analysis including Rayleigh fading channels and individual interferences from adjacent cells. The simulation result obtained by 30000 iterations with the same PRACH power setting. From the figure, we can verify the analysis is valid for Rayleigh fading environments, and hence use the analysis to find the optimal PRACH power setting in the self-optimization process.

IV. SON Process and Performance Evaluation

We propose a self-optimization process of the PRACH power setting, which is composed of two steps. The first step is the optimization process that solves the problem in (3) with given input parameters such as IoT_j, γ_{prach}^{th}, γ_{pusch}^{th}, and p_{pusch}. The exhaustive search is executed to find the optimal power setting that satisfies the objective function and constraints because the number of possible power settings is limited only to 64. The next step is that eNB periodically updates its own average IoT through the moving average scheme and exchanges the information with adjacent cells and then, the optimization process is conducted again.

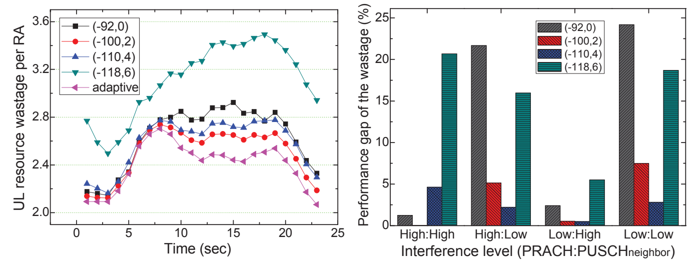
A. Simulation Setup

In order to evaluate the self-optimizing process, we apply the synthesized IoT as depicted in Fig. 5-(a). IoT level varies every frame (10 ms) and the deviation follows Gaussian distribution. Each cell experiences a different time-varying IoT, and we evaluate experiments with high-IoT and low-IoT, which are average 10 dB and 3 dB, respectively. We assume each eNB exchanges the moving average of IoT with neighbor eNBs every 1 second (100 frames), where the averaging window size is also 1 second. Meanwhile, as described in Fig. 2 the influence of PRACH signal exponentially increases as the random access UE moves to the cell-edge while the effect of cell-center UE is negligible. Therefore, we focus on



(a) Synthesized IoT at cell 1 (b) ITRP adaptivity

Fig. 5: Generated IoT and ITRP adaptivity



(a) Comparison of the sum wastage (b) Performance gain of adaptive ITRP

Fig. 6: Simulation result.

the cell-edge random access UE that is randomly generated in the outside of 95 % of cell radius. The other system parameters is defined in Table I.

TABLE I: System Parameters

Parameter	**Value**
Inter-cell distance	860 m
Cell layout	Hexagonal 7-cell
P_{max}	24 dBmW
N_0	-174 dBm
$p_{0,prach}$	$-120 \sim -90$ (dBm)
ΔP	0, 2, 4, 6 (dB)
PUSCH target SNR	6.6 dB
Noise figure (eNB side)	5 dB
$Load_{PUSCH}$	Full load
Path loss (dB)	$128.1 + 37.6log_{10}(d), d[km]$
Fading model	Rayleigh fading
Uplink power control	Full compensation
Simulation time	24000 ms

B. Simulation Result

SON process of the PRACH power setting, which automatically finds the optimal value according to time-varying IoT level is illustrated in Fig. 5-(b). Fig. 6-(a) shows a snapshot of the performance of the proposed SON process compared with fixed PRACH power setting, and Fig. 6-(b) presents the average performance gain, which is the ratio of the additional wastage that the fixed power causes to the wastage that the SON process brings about for various IoT levels. For example, {High:Low} on x-axis of the figure, means that the IoT level at PRACH of the cell in consideration is high and the IoT level at PUSCH of neighboring cells is low. SON process always achieves the best performance to find the optimal power setting for various time-varying IoT levels while the best fixed power setting changes as the condition of IoT level changes. For example, (-100,2) is a good choice for {High:High}-IoT level but is not the best choice any more for {Low:Low}-IoT level.

V. Conclusion

In this paper, we propose an adaptive algorithm to determine PRACH power setting composed of the initial target received power (ITRP) and power ramping step considering time varying interference over thermal noise (IoT). First, we formulate an optimization problem to minimize the uplink resource wastage such as PUSCH outages at adjacent cells caused by random access preambles and PRACH outages due to the preamble detection miss. We consider constraints of the ramping number and the detection failure probability with the problem. We show the tradeoff relationship between adjacent cell's uplink outage and PRACH outage of the cell in consideration according to the PRACH power setting. There exists a cross point that minimizes the sum resource wastage, and each eNB can find the optimal power setting from the formulation by exchanging current IoT values with its adjacent cells. We demonstrate via simulations that the optimal PRACH power setting can be adapted to the frequent change of IoT through the periodic updates.

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