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Capacity-based compressed mode control algorithm for inter-system measurements in UMTS system

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Abstract The Inter-system handover between UMTS and GSM is one of the key features in the third generation UMTS cellular system. The compressed mode, with variable transmission gaps and power levels, is standardized to support the inter-frequency/system handover. In this article, a capacity-based compressed mode algorithm which considers potential impacts on the capacity and the priority of operating the compressed mode measurement is proposed to reduce the use of system resources while maintaining the UMTS-to-GSM border-cell handover quality. The performance of the proposed algorithm will be studied based on UMTS simulation platform.

Keywords Inter-system handover · Compressed mode · UMTS · GSM · Capacity · Scheduler

1 Introduction

In order to support different applications and high transmission rates, various 3G technologies have been standardized. Universal Mobile Telecommunications System (UMTS) [1], one of 3G systems, has been deployed to overlap with existing Global System for Mobile Communications (GSM) systems [2]. In an early deployment, UMTS will be deployed mostly in urban areas to save initial capital costs. However, a user originally initiated in the border cells of UMTS might need to be handed over to GSM systems in order to achieve a seamless migration from UMTS to GSM. To resolve this inter-system handover, three methods have been considered: The first method is Blind Handover. The Blind Handover chooses a target cell blindly without any measurement. Even this method can speed up the handover process, a low handover success rate could happen due to the blind assignment. The second method is Dual-system Transceiver designs. This method will increase the hardware complexity and might not be suitable when there are more than two co-existing systems. Finally, the third method called Compressed Mode [3] is proposed to interrupt the current connection in order to measure other systems' RF conditions. In this article, the study will be based on the compressed-mode operation for the inter-system handover.

Many articles have studied the performance of the compressed-mode operation. Gustafsson et al. [4] provided the formula of the transmission rate and relative parameters to generate transmission gaps. The issues of triggering criteria for the compressed mode were also studied. In [5], as compared to the event-triggered compressed modes, with the cost of extra overhead, the periodic-triggered algorithm has a higher handover success rate. Zhang [6] suggested that the pilot-to-interference ratio, *Ec/Io*, is suitable for high traffic load and the received signal code power (RSCP) is suitable for low traffic load. A method which combined pilot *Ec/Io* and pilot RSCP triggering methods was proposed to guarantee border-cell handover performance under different traffic loads. The relationship between the compressed-mode gap patterns and the measurements of GSM carriers were considered in [7, 8], in which the required handover time for different transmission gap patterns was investigated. Holma and Toskala [1]

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further quantified the degradation in the capacity and coverage by increasing the transmission power if higher transmission rates are assumed during compressed frames. Some discussions in 3GPP TSGR4 meetings also addressed different performance impact scenarios [9–11]. Although above articles have pointed out related performance impacts, no proper solution is proposed. In this article, to manage the capacity impact while maintaining a high border-cell hand-down success rate, a capacity-based control algorithm that suspends users who have better RF conditions and sufficient GSM channel measurements from operating the compressed mode is proposed.

The organization of this article is as follows: Sect. 2 describes the overview of the compressed mode and related performance issues. The parameters of the compressed mode and the proposed capacity-based control algorithm will be investigated in Sect. 3. Section 4 will discuss the simulation environment and related assumptions. In Sect. 5, the simulation results will be evaluated. Finally, conclusions will be drawn in Sect. 6.

2 Overview of compressed mode

In UMTS, the compressed mode is considered for the inter-system handover. In [3], following three methods are suggested:

a. Reducing the spreading factor by two
   The first method is to double the transmission rate by reducing the spreading factor by two [1]. The time (transmission gaps) saved from the acceleration of the transmission rate will be used for measuring other systems' RF conditions. In this method, more power might be needed due to the increase of the transmission rate.
b. Puncturing
   The second method is to puncture redundancy bits from the associated channel coding. This method modifies only the channel coding rate but keeps the existing spreading factor and transmission rate unchanged. Due to the limitations of physical channel formats and channel coding rates, this method applies only to downlink transmission and is more suitable for short transmission gaps which might have the problem of sufficient measurements of other systems.
c. Higher layer scheduling
   Finally, besides of increasing the speed of the physical layer transmission, the data can be manipulated at a higher layer for non-real time data services or voice services which have enough silent periods. Since data bits can be rescheduled, transmission gaps can then be generated in non-scheduled periods for non-real time services especially.

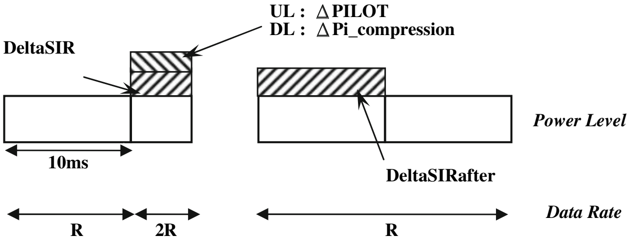

Fig. 1 Power increasing scenario in the compressed mode

Due to the limit ations of implementing the "puncturing" and "higher layer scheduling" schemes, the method of "reducing the spreading factor by two" is chosen for remaining studies.

In the compressed mode, transmission gaps are used to measure other systems. As depicted in Fig. 1, to maintain the same transmission data within a period of time, the transmission rate needs to be increased in order to compensate those "no transmission" gaps. Considering both the higher transmission rate and no power control during those transmission gaps, the system should increase the transmission power on both the downlink and uplink to overcome unpredictable channel variance during the compressed frame and next frame by DeltaSIR and DeltaSIRafter [12]. Besides, the mobile will also increase the transmission power by ΔPILOT and ΔPi to compensate the reduction of pilot bits (used for synchronization) on the uplink and downlink respectively [12].

Although the compressed mode is designed for the inter-system handover, the following performance could also be impacted:

a. Coverage
   If more power is needed to achieve the same QoS during the compressed-mode operation, the budget of the maximum path loss will be reduced. As studied in [1], the uplink path loss will be reduced by 2.3 dB if the compressed frame is operated once every two frames.
b. Capacity
   For the same reason, the capacity will be reduced due to the increase of the transmitted power during the compressed frames. A higher bit-energy-to-noise-density ratio, E_b/N_0, is required to maintain the same quality. From [1], the capacity will be reduced by about 2% even only 10% of users are operating the compressed mode once every three frames.
c. Code space shortage problem
   When the method of "reducing the spreading factor by two" is applied, the available code space will be reduced. In this case, there might not have enough codes to support all active users especially for high data rate users [13, 14]. Normally, the capacity should

be limited by RF not Walsh Code numbers (orthogonal codes). Taking voice as an example, typically in UTMS, the average capacity for 7.9 kbps codec is in the range of 80–85. With the handover overhead factor of 1.3 (needs multiple codes to support one user), the total required codes are in the range of 104–110. In this case, the required codes are still less than the UMTS code number of 128 (to support 7.9 kbps) but the code space management might have an issue when users are in the border cells where users in the compressed-mode operation will require twice the code space (consecutively). In that case, to make sure that users can have proper compressed-mode operation, the system needs to reserve extra code space for each user when it moves into the border cell. As a result, there still will have the chance of running out of the code space. The problem could be even more serious when high data rate users are co-existed.

In following studies, we will focus only on the solution of resolving the capacity impacts and the performance of inter-system handover.

3 Capacity-based compressed mode

In this section, the uplink and downlink capacities are first discussed. The compressed-mode format including the gap generation method, triggering criteria, and gap pattern will then be investigated. Finally, the capacity-based compressed-mode control algorithm is proposed.

3.1 The uplink and the downlink capacity

As discussed, the increasing power in the compressed-mode frames will reduce the capacity. To calculate the uplink capacity, the required bit-energy-to-interference ratio (E_b/I_0) can be calculated approximately in Eq. 1. For simplicity, the same service and same received power at the base station are assumed for all mobiles.

$$\frac{E_b}{I_o} \approx \frac{S \cdot PG}{FN_{th}W + \alpha[(1+\beta)(1+\gamma)(N-1)S + N_{CM}\Delta S]} \tag{1}$$

where E_b is the received bit energy, I_o is the total interference, S is the received power at the base station from each mobile station, PG is the processing gain, F is the noise figure, N_{th} is the thermal noise power density, W is the transmission bandwidth, α is the voice activity, β is the adjacent cell interference factor, γ is the overhead power factor, N is the number of users, N_{CM} is the number of users who are in the compressed mode, and Δ S is the average increasing power from the compressed-mode users.

From Eq. 1, the capacity, Nc, can be calculated and rewritten in Eq. 2, where $(\frac{E_b}{I_o})_{target}$ is the target bit-energy-to-interference ratio.

$$\begin{aligned} N_C \approx & \frac{PG}{\alpha(1+\beta)(1+\gamma)(E_b/I_o)_{target}} \\ & + 1 - \frac{FN_{th}W}{\alpha(1+\beta)(1+\gamma)S} - \frac{N_{CM} \cdot \Delta S}{\alpha(1+\beta)(1+\gamma)S} \end{aligned} \tag{2}$$

As shown in Eq. 2, the capacity will be reduced by $(N_{CM} \cdot \Delta S/(1+\beta)S)$ during the compressed-mode operation. When the maximum allowable cell loading (noise rise) and the maximum power budget of the mobile station have reached, the received power S will be limited by users who located at the cell edge.

For the downlink capacity, the capacity is limited by the maximum power budget, calculated in the Eq. 3:

$$P_{tot} = P_{OH} + \sum_N [\alpha \cdot P_i \cdot M_i] \le P_{\max} \tag{3}$$

where P_{tot} is the total transmitted power from the base station, P_{OH} is the overhead power, N is the number of users in the cell, α is the voice activity, P_i is the base station transmitted power for user i, M_i is the multiplier of the increasing compressed-mode power for user i, and P_{max} is the maximum power budget. As known, the P_i is the function of $(\frac{E_b}{I_o})_{target}$, path loss, and the interference received at the user equipment (or mobile station). The M_i is equal to 1 when the compressed mode is not operated and is greater than 1 when the compressed mode is operated.

It is obvious that, for both the uplink and downlink, the capacities will be reduced when the number of the compressed-mode users increases. In this study, the proposed control algorithm will consider only the downlink capacity due to the following reasons:

1. Only the base station can acquire the information of all users' compressed-mode profiles. The base station can execute the capacity-based compressed mode by sending messages to all mobiles in the cell to control the compressed-mode operation.
2. In the asynchronous data transmission, usually the required transmission data from the downlink is more than that on the uplink. As a result, the capacity will be limited on the downlink especially when multi-media services are also supported.

3.2 The compressed-mode format

The compressed-mode format is composed of the gap generation method, triggering criteria, and gap pattern.

3.2.1 Gap generation method

As discussed in Sect. 2, the method of "reducing the spreading factor by two" is chosen for this study.

3.2.2 Compressed-mode triggering criteria

The pilot *Ec/Io* is the measurement used for UMTS soft handover trigger. However the pilot *Ec/Io* is not suitable for the compressed-mode trigger due to the border cell effect. In border cells, the pilot signal and interference (mostly from the same sector) are under the same fading condition, thus the pilot *Ec/Io* will hold the value until it hits the noise limit. Figure 2 shows the curves of *Ec/Io* versus the distance in a center cell and border cell. It is obvious that the pilot *Ec/Io* curve stays flat in the border cell regardless of the distance. The same border cell effect is also observed in [15].

To ensure in-time measurement and to avoid unnecessary compressed-mode triggers, the pilot-received-signal-code power (RSCP) is chosen. As known, the RSCP is the received pilot power and its strength will be directly inverse proportional to the path loss. To have a fair comparison, a common set of thresholds are used to trigger and to stop the compressed-mode operation. A threshold hysteresis and timer are also included to avoid the ping-pong effect due to signal fluctuation.

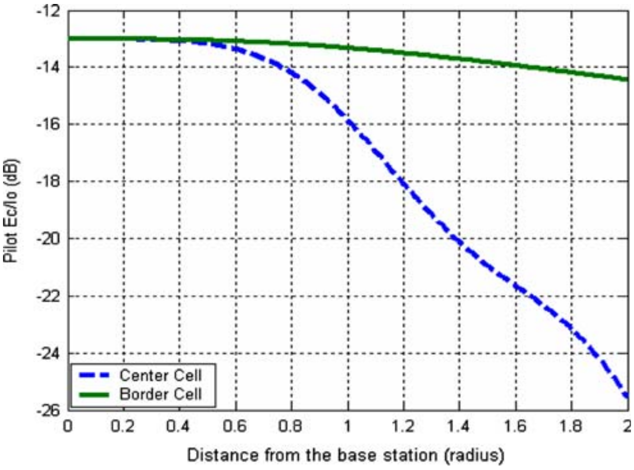

Fig. 2 The pilot *Ec/Io* curve in center and border cells

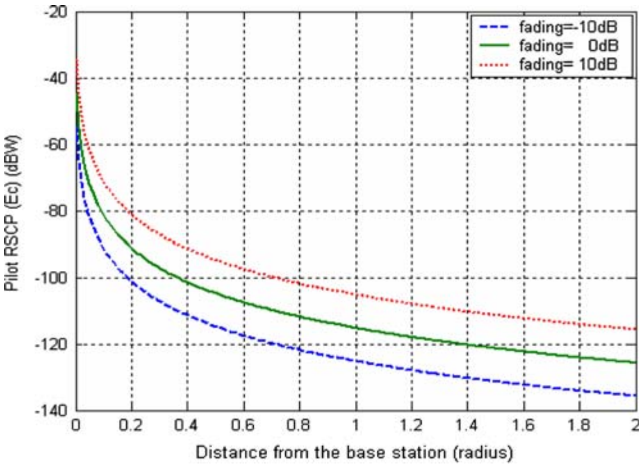

Fig. 3 The relationship of pilot RSCP and distance

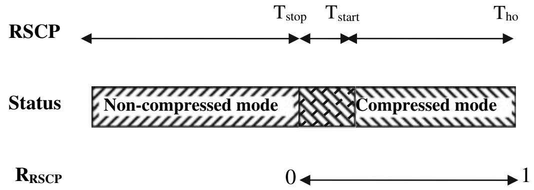

Fig. 4 The relationship of R_{RSCP} and distance

As mentioned, RSCP will be used as the triggering measurement for the border-cell inter-system handover. The relationship of pilot RSCP and the distance from the base station is depicted in Fig. 3. When a mobile is close to the base station, the curve shows the exponential increase of the RSCP in dB scale. When the mobile is away from the base station the curve tends to stay linear. For stability, the compressed-mode operation should be considered during the linear relationship. As calculated in Eq. 4, the pilot RSCP ratio (R_{RSCP}) represents the effective distance in between the handover trigger and no compressed-mode region.

$$R_{RSCP} = \frac{T_{stop} - RSCP}{T_{stop} - T_{ho}} \tag{4}$$

where T_{stop} is the threshold to stop the compressed mode and T_{ho} is the threshold to trigger the border-cell handover.

The compressed mode operates only in between T_{stop} and T_{ho} (R_{RSCP} is ranged from 0 to 1). The compressed-mode operation will stop when R_{RSCP} equals to 0 and will hand down to GSM when R_{RSCP} equals to 1. The relationship between R_{RSCP} and $RSCP$ is shown in Fig. 4, where the T_{start} is the threshold to start the compressed-mode operation. The difference between the T_{stop} and T_{start} is the hysteresis for avoiding the ping-pong effect.

3.2.3 Gap pattern to measure GSM carrier

In GSM, only Frequency Correlation Channel (FCCH), Synchronization Channel (SCH), and Broadcast Channel (BCH) are transmitted at all time. To be useful, the measurements of GSM carriers and Base Station Identity Codes (BSICs) [14] will be on FCCH and SCH. However, the gap patterns in UMTS specification [14] do not to match with

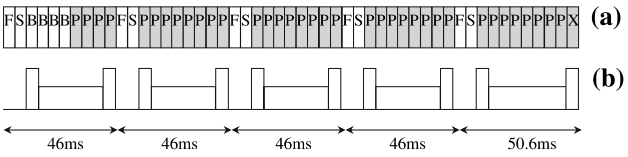

Fig. 5 (**a**) GSM channel structure (**b**) compressed mode gap pattern

GSM timing structure. Ideally, the measurement gap in GSM should be 9.2 ms in every 46 ms. To have the proper measurement, in UMTS, the gap time of 14 slots in every 5 frame (9.3 ms in every 50 ms) is chosen to match with GSM control frame structure. The GSM channel structure is depicted in Fig. 5(a) and the corresponding gap pattern is depicted in Fig. 5(b).

3.3 The proposed capacity-based compressed-mode control algorithm

In this section, a new capacity-based compressed-mode control algorithm considering different priorities of users in terms of the RF conditions and the number of effective GSM channel measurements will be proposed. Before discussing the proposed algorithm, we will first investigate two proposed compressed-mode patterns: the reposition-based compressed-mode pattern and suspension-based compressed-mode pattern.

When a mobile needs to measure other systems such as GSM, the mobile can measure only at a few measurable time slots. As a result, all users in border cells will execute the compressed mode more or less simultaneously in order to match with measurable time slots as depicted in Fig. 6(a). As discussed, the increasing power from all users in the compressed-mode duration could cause a serious impact on the capacity. To reduce the impact, two patterns are proposed and depicted in Fig. 6(b) and (c). The first pattern, reposition-based compressed-mode pattern, is to separate the transmission gaps in order to spread out the increasing power. The second pattern, suspension-based compressed-mode pattern, is to reschedule users' orders in executing the compressed-mode. In the first proposed pattern, there is no guarantee that the new measurement interval can match properly with the actual transmission slots of GSM systems. As a result, the suspension-based compressed-mode pattern will be chosen for the proposed control algorithm.

The proposed capacity-based compressed-mode control algorithm is designed to limit the aggregate power level in the compressed-mode frame by suspending low priority users from operating the compressed mode. When the base station power budget is reached, regardless of the user applications, users who have relatively better RF conditions and more GSM measurements will have higher chances to be suspended. Due to the mobility, all users (of different applications) will need to be handed down to the GSM system. In this case, to maintain a proper hand-down success rate, the priority of different applications could be the same in compressed-mode suspension.

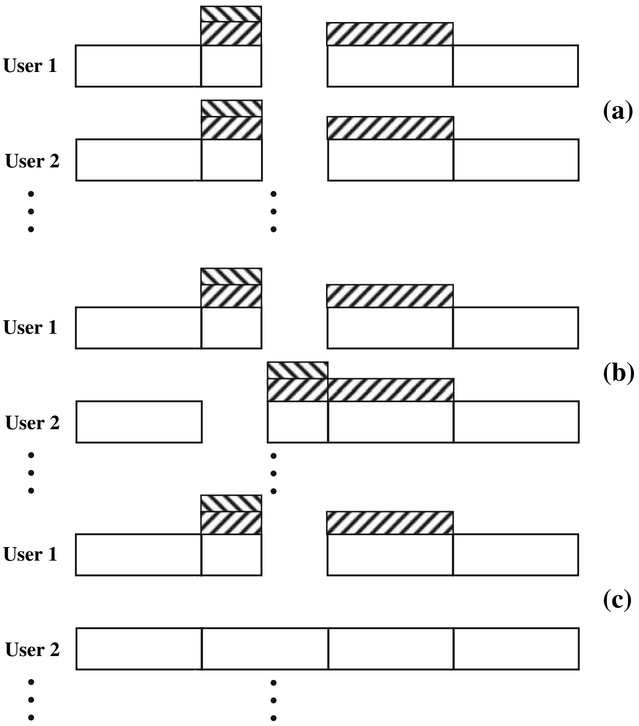

Fig. 6 The compressed-mode schemes (**a**) Normal compressed mode at simultaneous time (**b**) Reposition based compressed mode (**c**) Suspension-based compressed mode

3.3.1 *Capacity-based compressed-mode control algorithm*

(1) In every frame, as shown in Eq. 5, the suspension factor $F_i(n)$ is calculated. The $F_i(n)$ is the function of the pilot RSCP ratio R_{RSCP} (from Eq. 4), aggregate measured GSM samples $N_{meas}(n)$, and the record of previous compressed mode action, $R_{suspend}$.

$$Suspension\ factor: F_i(n) = \frac{N_{mean,i}(n-1)}{R_{RSCP,i}{}^{k}(n)} \times R_{suspend,i}(n) \tag{5}$$

$$R_{suspend,i}(n) = \begin{cases} a, & \text{suspended in the previous compressed-mode frame} \\ ma, & \text{otherwise} \end{cases} \tag{6}$$

As shown, the algorithm prefers to suspend the users who are close to the base station (small R_{RSCP}) or have larger GSM carrier measurements, N_{meas}. The factor k will emphasize the effective distance, R_{RSCP}. From the proposed algorithm, the scheduler intends to maintain the same ratio of $\frac{N_{meas}}{R_{RSCP}^{k}}$ first; it tries to balance the aggregated measurements and the effective distance. The $R_{suspend}$ is designed to prevent suspending compressed-mode frames consecutively from the same user. It will be equal to '*a*' when previous compressed-mode frame has been suspended and will be equal to '*ma*' otherwise. We believe that continuous suspension may delay the effective measurements especially when handling an emergent handover.

(2) The second step is to compare the current base station's transmitted power and the suspension power threshold, P_{thr}. The system will allow operating at a regular compressed-mode operation if the base station power, P_{Bt}, does not exceed the threshold P_{thr}. In other words, the proposed suspension algorithm will be triggered only when the system is loaded which might have a negative impact on the connection performance.

The flow chart of the capacity-based compressed-mode control algorithm is also depicted in Fig. 7. The base station first collects the information of the compressed-mode users and then on every frame it calculates the suspension factor of all users in the compressed-mode operation. The base station examines its transmitted power and decides whether to implement the proposed algorithm to suspend the compressed-mode users. It is worth to emphasize here that in our proposal the control is not to delay the handdown process but to reduce the total number of the simultaneous compressed-mode frames when the system is loaded. The most important is that the proposed algorithm suspends most users who have relatively better RF conditions or sufficient GSM measurements. In other words, for those users who really need to be handed down to GSM system will have less chance to be suspended. So, in general, the handdown process would not be delayed by implementing the proposed algorithm.

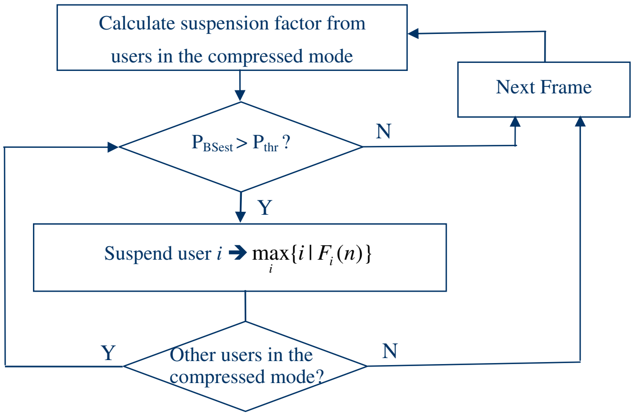

Fig. 7 The flow chart of capacity-based compressed mode

4 Simulation platform

As depicted in Fig. 8, based on MATLAB, the simulation is established with 19 UMTS cells and all UMTS cells are surrounded by GSM Sea. Each UMTS cell has three sectors and the angles of the antennas are 0°, 120°, and 240°. The coverage can be calculated by the uplink link budget and propagation model COST-231, listed in appendix Tables 1 and 2 respectively.

Some important simulation parameters are listed in Table 1. The maximum base station power budget is assumed to be 20 W (including 4 W of the overhead power). For the mobility model, mobiles are uniformly placed in each sector initially. All mobiles will keep the same moving speed during the simulation period of 100 s. Here, we assume that the moving speeds are followed by a uniform distribution, ranged from 50 to 100 km/hr by assuming border cells are located in the rural areas or suburban areas.

After each sample period, users will change the moving direction followed by Gaussian distribution with a zero mean and the standard deviation of 1.6 degrees. Based on Monte Carlo simulation, for the same mobility model, each simulation point is generated based on the average of 30

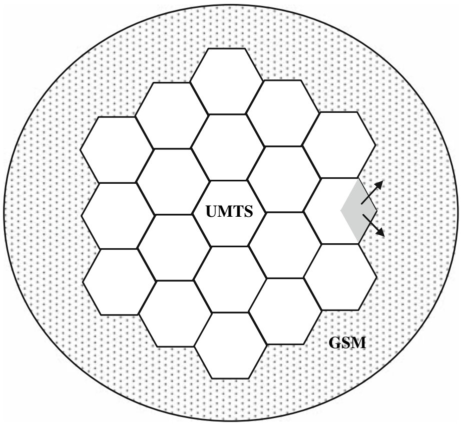

Fig. 8 The simulation platform

Table 1 The simulation parameter

Simulation parameter	
Radius	0.95 Km
Mobile speed	50–100 Km/hr
Bandwidth	3.84 Mcps
Bit rate	12.2 Kbps
Required Eb/No	4.57 dB
Voice activity	0.48
Maximum transmit power	20 W
Transmit overhead power	4 W (3 W for pilot)

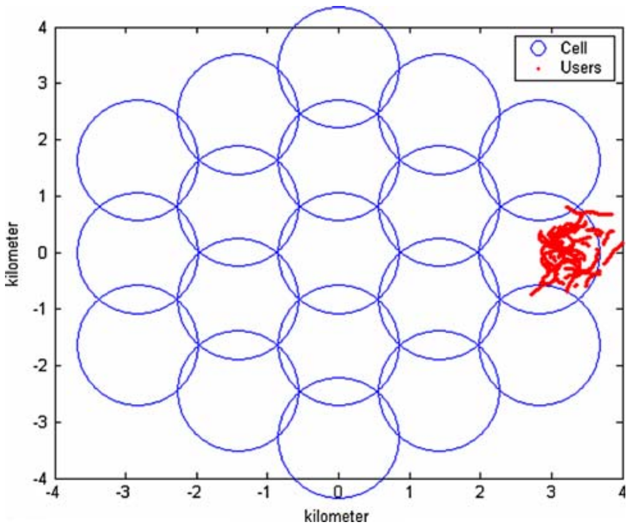

Fig. 9 The mobility scenario

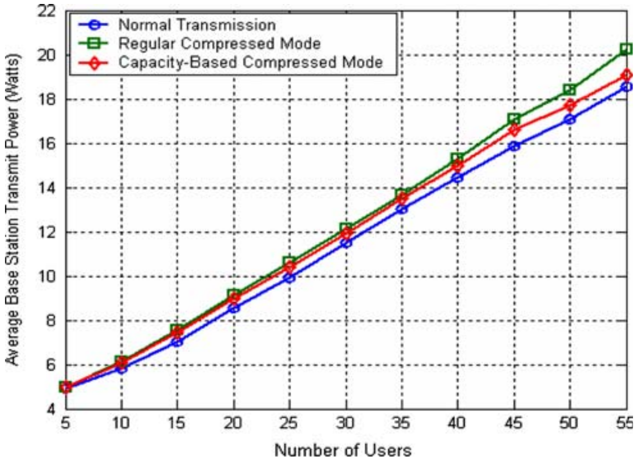

Fig. 10 Average base station transmit power

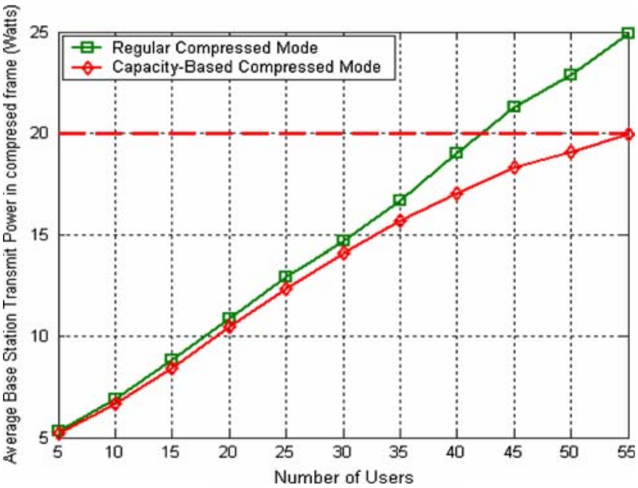

Fig. 11 Average base station transmit power in the compressed frame

runs for each fixed number of users, depending on the number of users, the mean performance will be stable after 10–15 runs. The trajectories of the mobile stations at the border sector are shown in Fig. 9. Other relative RSCP parameters are listed in Table 2. The threshold settings are based to the distance from the base stations with zero fading. For the baseline performance, the simulation starts the compressed-mode operation when the pilot RSCP is smaller than –108 dBW and stops the compressed mode when the pilot RSCP is larger than –104 dBW. The handover is triggered when the RSCP is smaller than –118 dBW for 500 ms.

5 Simulation results

In the simulation, the UMTS compressed-mode performance in terms of the required base station transmitted power, connection quality (best pilot *Ec/Io*), and the number of GSM channel measurements will be investigated.

Considering all users at all time, Fig. 10 shows the average transmission power at different loadings. As expected, the regular compressed mode needs more power than normal transmission. With the proposed suspension control, the transmission power of the capacity-based compressed mode will be lined in between above two operations. Since the compressed mode operates only once every five frames (as discussed in the subsection of the gap pattern to measure GSM carrier), to understand the instant impact from the compressed frame, Fig. 11 shows only the impacts on the compressed frame duration. As shown, the base station transmission power in the regular compressed-mode operation exceeds the tolerable maximum power budget (20 W) when the number of users is larger than 42. Using the proposed algorithm, the capacity can be improved to 55. Here, the improved capacity might be

Table 2 Compressed mode triggering threshold

Threshold	Value	Distance
Compressed mode start threshold for pilot RSCP	–108 dBW	0.5*radius
Compressed mode stop threshold for pilot RSCP	–104 dBW	0.6*radius
Handover triggering threshold for pilot RSCP	–118 dBW	Radius
Time to trigger handover	500 ms	

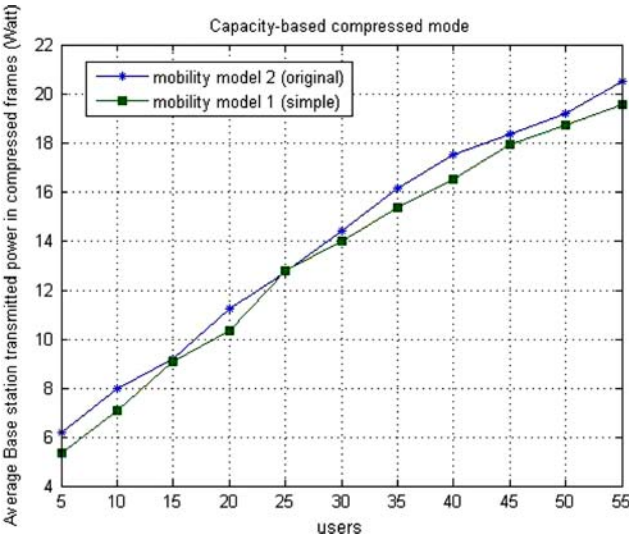

Fig. 12 Comparison between two mobility models

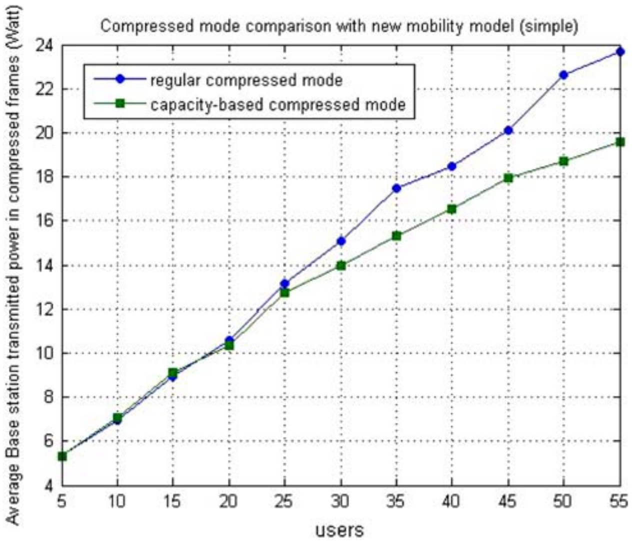

Fig. 13 Average base station transmit power in the compressed frame (with new mobility model)

different with different mobility models and user applications. To show that, we have considered another mobility model, in which the moving speed is fixed at 60 km/hr. After each sample period, mobiles have the probability of 20% to change to a new direction, ranged from –π/4 to π/4 uniformly. As compared to previous mobility model, from Fig. 12, the capacity, resulting from the new mobility model, is different but close to the capacity from the old mobility model. As for the power saving, the percentage of the power saving from the compressed-mode operation is also different (17.5% as compared to 20% in the old mobility model) but the trend is similar. As a result, the capacity improvement should be used for relative comparison only. Besides, typically, a more detail GSM channel structure or different gap patterns will also help to reduce the impact on the capacity. Since the proposed algorithm will be triggered to suspend users only when the cell loading (BS power budget) exceeds a threshold, the algorithm can apply to any new compressed-mode patterns and still reduce the capacity impact when the cell loading is high.

Considering both the break point at 42 for the regular compressed-mode algorithm and the effect by implementing the capacity-based compressed-mode control algorithm, the user number of 45 is chosen in the following plots. A further improvement is expected if more users are considered (Fig. 13).

From Fig. 14, the best pilot *Ec/Io* of the regular compressed mode is less than that in the normal transmission by 1 dB–2 dB. Even the best pilot *Ec/Io* of the proposed capacity-based compressed mode is again between the previous two scenarios, the proposed algorithm improves the best pilot *Ec/Io* especially from those users who are in worse RF situations (≤8 dB). This is because the algorithm will be triggered more often when the average pilot *Ec/Io*is decreased due to the increase of the total base station transmitted power. It is possible that different transmission rates will have different capacity impacts. If the suspension priority can be chosen based on transmission rates, we expect the capacity saving will be even more. In our proposal, besides of having the control in the capacity during the compressed-mode operation, another important control is to suspend compressed-mode frames to make sure there are still sufficient GSM channel measurements before the handdown process. In that case, if users who transmitted at higher rates will be suspended more often than others, those high-date-rate users might have higher failure rates in UMTS/GSM handdown. So, to achieve an equal handdown success rate, users with different transmission rates will be treated equally in our proposed algorithm.

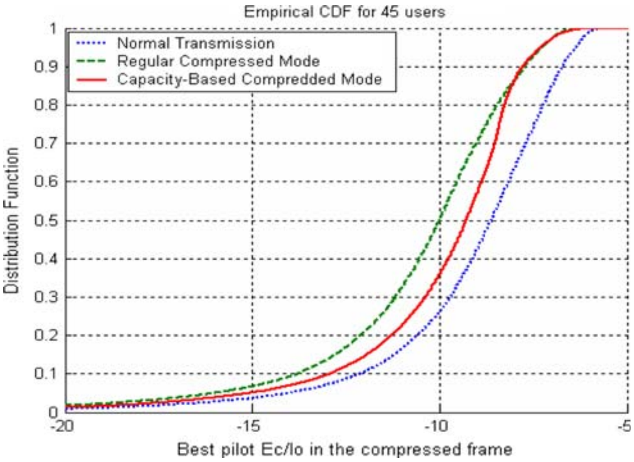

Fig. 14 The best pilot *Ec/Io* distribution function for 45 users

Next, we will examine whether the high suspension ratio will degrade the handover success rate in terms of the number of required GSM Channel measurements. Assuming the maximum GSM neighbor list has 32 carriers. Among those carriers, there should have eight stronger carriers which need to have BSIC verification and reverification processes [16]. If for each carrier measurement, it needs at least three samples, the expected minimum number of GSM carrier measurement samples is equal to 144 = (32 + 8 + 8)*3. With different number of users, the number of GSM Received Signal Strength Indicator (RSSI) samples before handing down to GSM systems is shown in Fig. 15. As shown, even the measured sample number decreases as users increase (due to the increase of the suspension rate), the average number of RSSI samples is still greater than the minimum number of required RSSI samples of 144. Also, from Fig. 15, if we normalize to 5-user case, the reduction percentage of RSSI measurements is close to 45% when reaching the RF limit.

Finally, we examine how the weighting factor *k* affects the performance. Since the proposed algorithm intentionally suspends users at better RF conditions, we expect higher *k* will force the suspension goes to users who are close to the base station and make the system harder to suspend those users who are in the hand-down region. As shown in Fig. 16, the average number of RSSI measurement samples (before GSM hand-down) will increase as the *k* increases but the associated standard deviation (STD) will also be increased. Even if we consider the STD, the number of RSSI samples is still greater than the minimum required number of the RSSI measurements. Also shown in Fig. 17, higher *k* allows more measurements (or lower suspension probability) when users are away from the base station (≤113 dB) and will reduce measurements when users are close to the base station.

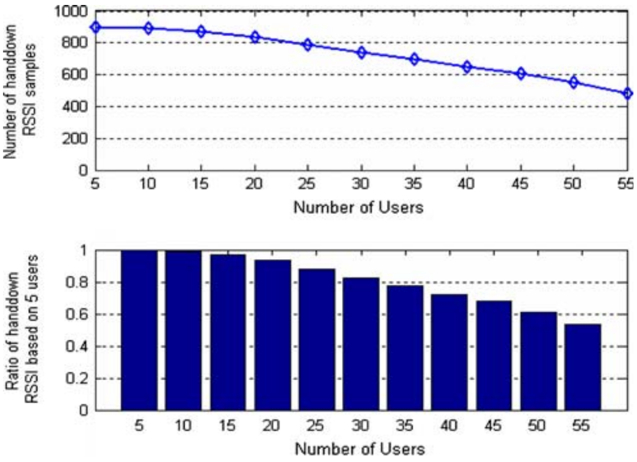

Fig. 15 The number of hand-down RSSI samples with loading ($k = 2$)

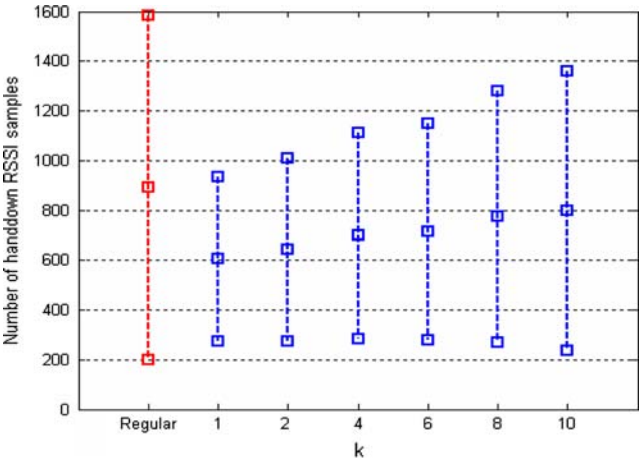

Fig. 16 The number of hand-down RSSI samples with different k (User = 45)

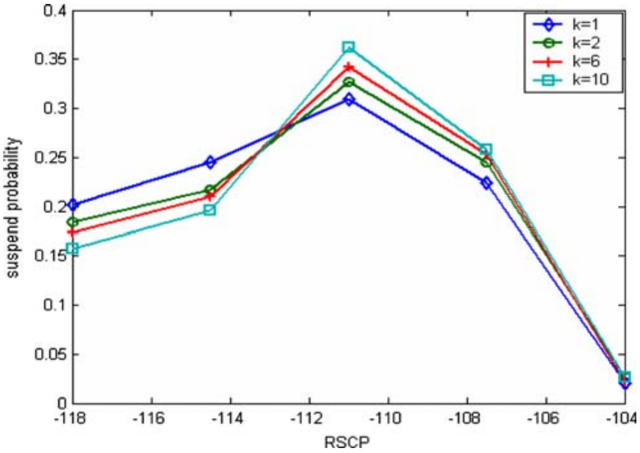

Fig. 17 The relationship of the suspend probability and RSCP with different k (User = 45)

6 Conclusions

In this article, to resolve the excessive transmission power, which directly affects the system capacity during the compressed-mode operation, the capacity-based compressed-mode control algorithm is proposed. By considering different RF conditions, the number of RSSI measurements, and the avoidance of continuous suspension, the proposed algorithm can effectively maintain the capacity by reducing the number of simultaneous compressed-mode measurements while keeping the more-than-enough measurements before handing down to GSM system. Furthermore, with different choices of power weighting factor *k*, users with different priorities in terms of the necessity of the border-cell hand-down can be easily separated. The proposed capacity-based compressed-mode control can also be further extended to a general control concept if user priority can be identified.

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7 Appendix

Table A1 Uplink link budget

Item	Symbol	Value	Units
Total TX power available	P_{TX}	21	dBm
TX antenna gain	G_{tx}	2	dB
Body loss	L_t	2	dB
TX EIRP per traffic channel	$P_{EIRP} = P_{TX} + G_{tx} – L_t$	21	dBm
RX antenna gain	G_{rx}	18	dB
RX cable and connector losses	L_{cable}	4	dB
Receiver noise figure	NF	3	dB
Temperature, kelvin	T	290	K
Boltzmann's constant	k_b	1.38×10^{-23}	(J/k)
Thermal noise density	$N_{density} = 10\log(k_b^{*}T)$	–174	dBm/Hz
Noise rise due to interference	N_{inte}	4.56	dB
Total effect of noise	$N_{eff} = NF + N_{density}$	–171	dBm/Hz
Bit rate	R_b	12.2	kbps
Information rate	$R_{dB} = 10\log(R_b)$	40.86	dBHz
Effective required E_b/N_o	E_bN_o	4.57	dB
RX sensitivity	$S_{RX} = N_{eff} + R_{dB} + E_bN_o$	–125.57	dBm
Soft handoff gain	G_{SHO}	4.5	dB
Fast fading margin	M_{ffad}	0.5	dB
Log normal fade margin	M_{log}	11.6	dB
In-building penetration loss	L_{pene}	16	dB
Maximum path loss	$PL_{max} = P_{EIRP} + G_{rx} – L_{cable} − S_{RX} + G_{SHO} – M_{ffad} – M_{log} – L_{pene}$	136.97	dB

Table A2 The parameter of the propagation model

Item	Symbol	Value	Units
Frequency	f_c	2000	MHz
Base station antenna height	h_{bs}	30	m
Mobile station antenna height	h_{ms}	1.5	m

$$L(urban)(db) = 46.3 + 33.9\log f_c - 13.82\log h_{bs} - a(h_{ms}) + (44.9 - 6.55\log h_{bs})\log d$$

$$a(h_{ms}) = (1.1\log f_c - 0.7)h_{ms} - (1.56\log f_c - 0.8)dB$$

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