Relays in HSPA+: Power Control and Mobility

Jason F. Hunzinger, Jilei Hou, Shengshan Cui
Corporate Research & Development
Qualcomm
San Diego, CA

***Abstract*—There is substantial and growing motivation to deploy wireless relays in 3G+ and 4G networks both in residential and commercial contexts to achieve significant coverage extension and capacity increases at potentially relatively low cost. However, relays operating in shared spectrum may introduce interference thus potentially counterbalancing gains, and conversely, relays requiring a dedicated resource (for access or backhaul) may raise issues of efficiency and load balancing including under or over use of either relay or macro (base station) resources. In this paper, we consider these issues and propose new power control and mobility algorithms to overcome these challenges. Results of our detailed system simulations are presented demonstrating how substantial gains in user experience, capacity, and coverage extension may be obtained in the context of HSPA+.**

Keywords-heterogeneous networks; mobility; multihop cellular; power control; relay

I. INTRODUCTION

Motivations to deploy relays in wireless networks may include: (1) extending coverage to indoor coverage holes or to poor coverage areas; and (2) increasing capacity, by cell splitting gain or targeting hotspots (see Fig. 1) [1-4]. While such goals may be sought via other means such as micro-cells or femtos, relays use a wireless *backhaul* (or *self-backhaul*) to a base station (NodeB) and thus avoid issues associated with wiring to the site including installation and maintenance cost (e.g. fiber to a pico cell or DSL for a home NodeB or femto) and may even be portable or mobile.

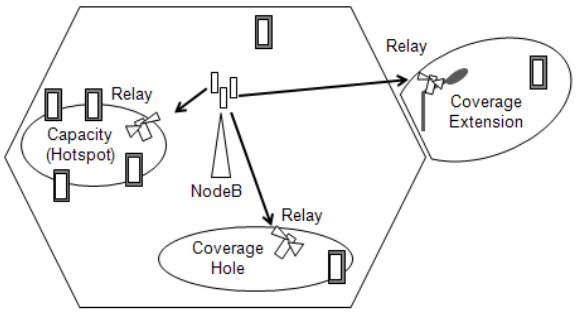


Figure 1. Motivations for relays: coverage and capacity.

Relays or *multi-hop heterogeneous* networks have thus recently been proposed for 4G networks [1, 2]. However, we proposed they may also be particularly applicable to evolving 3G+ networks, in both green field and established layouts, such as HSPA+ (releases 7, 8 and beyond) [5].

In this paper, we focus on relays that use the same wireless technology for backhaul (first hop: base station to relay) as for access link (second hop: relay to user). Such a relay design expands possibilities for resource sharing (of time, code or frequency blocks). First, a relay may share wireless resources (e.g. downlink carrier frequency) used for access link with macro cell base station access links. Second, a relay may share wireless resources for backhaul with access links (whether relay's, macro's or both). Conceivably, any of those links may be statically or dynamically allocated dedicated resources as part of intercell interference coordination (ICIC) techniques along with joint processing of serving and interfering signals [6]. Rather, motivated by simplicity we consider frequency resource sharing for HSPA+ without special coordination.

However, sharing resources in a relay context presents potential interference issues depending on the resource sharing scheme (see Fig. 2). If backhaul shares spectrum with access links (case I), uplink and downlink transmissions between relay and macro on the backhaul may interfere with (or limit bandwidth for) transmissions between macros and their directly-served users. Similarly, if relay access links share spectrum with macro access links (case II), a relay's downlink transmissions to users may interfere with macro transmissions to macro-served users. Both concerns arise when all links share resources (case III). A relay will typically have a lower transmit power and smaller footprint than a base station (NodeB) but this does not prevent interference.

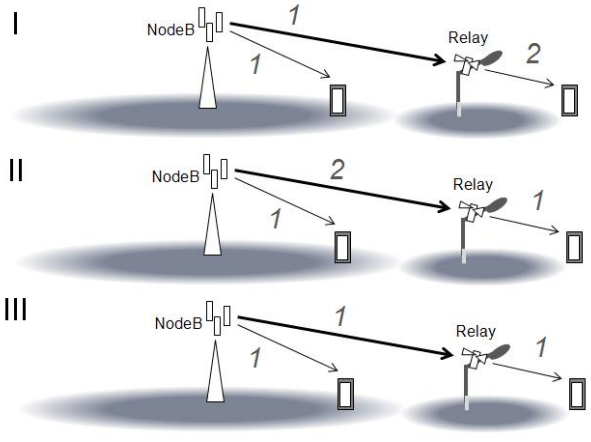


Figure 2. Division of resources (1 and 2) in relaying schemes: (I) backhaul and macro access share 1, (II) relay and macro access links share 1, (III) relay backhaul and access link share 1 with macro access links.

Yet, if we attempt to avoid interference issues by allocating dedicated spectrum for backhaul links, load balance and efficiency may be sacrificed. For example, if there are few users served by relays while many users are served by macro base stations, dedicated backhaul spectrum may be underutilized. Of course, the converse may also occur.

Here, we consider how distributed dynamic relay power control and mobility (association to macro or relay) may present practical alternative solutions. While typical power control or handover bias methods may seek to limit interference leaked beyond a coverage area, limit interference due to closed-access femto nodes or extend range, we formulate a sharing problem for open-access relays in terms of distributed balancing of user benefits and detriments and in relation to the relay wireless backhaul. Specifically, we propose dynamic relay power control may alleviate interference when relays share resources with macro links (cases II and III), while dynamic user mobility may address efficiency when backhaul shares resources with macro access links (cases I and III). We propose straight-forward backward-compatible algorithms and present results of our detailed multihop heterogeneous HSPA+ system model.

II. Interference and Relay Power Control

A. The Relay Interference Problem

Interference issues are arguably most pronounced in an in-band relay deployment (case III) where all links use the same resource/spectrum or carrier (frequency). Given any relay transmit power level, we may classify users in four groups (see Fig. 3) to analyze interference and power control effects:

- Benefitted Associated (BA) users
- Degraded Associated (DA) users
- Degraded Non-associated (DN) users
- Benefitted Non-associated (BN) users

We use the term *associated* in reference to the relay: a user that would be served by the relay is an *associated* user. We define a *benefitted* user as a user whose performance improves with the addition of a relay as compared to degraded.

Indeed, it is even possible for a relay to introduce interference to an extent that overall system performance with the relay degrades. Often, options for relay placement are limited or careful deployment planning may be costly. So, we may naturally consider adjusting power. But, if we lower relay power we may not necessarily improve matters. We may convert a DN user to a BN user (better) but also convert a BA user to a DA user (worse). Moreover, we may end up with no users on the relay, transmitting overhead and wasting dedicated backhaul resources.

While it may at first seem counterproductive, suppose instead we increase relay power. We may convert a BN user to a DN user (worse) but also convert a DA user to a BA user (better). Moreover, we may decrease load on a macro base station, which may help if the relay is not overloaded. If there are no nearby BN users, risks with raising power may be less.

We may thus observe that the effect of lowering or raising transmit power, in terms of improvement or degradation, generally depends on the distribution of active users and their geometries (or signal-to-noise ratios). Unfortunately, this also depends on the relay's power. Complicating this is that users are typically mobile so active user density and distribution in the coverage area changes. Moreover, if we reduce power, we reduce range and the ability of a relay to collect information from users at or beyond its current borders.

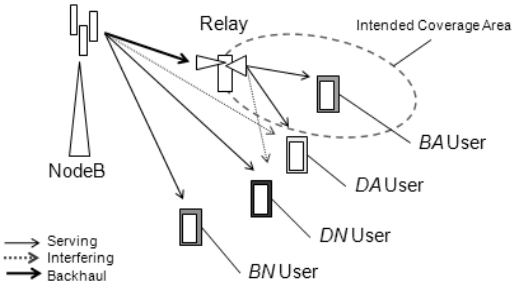


Figure 3. Classification of users according to impact from a relay and macro.

B. Dynamic Relay Power Control

To solve the above problems, we propose a model that is invariant with relay power so that if we change the power dynamically, we can continue to use statistics collected for our power control algorithm. To do so, we first define Equivalent Path Loss (EPL) for a relay *r*'s transmission to a user *u* as the difference between relay pilot transmit power *x(r)* and the relay's receive signal code power *y(u,r)* reported by a user *u*,

$$EPL(u) = x(r)-y(u,r). \quad (1)$$

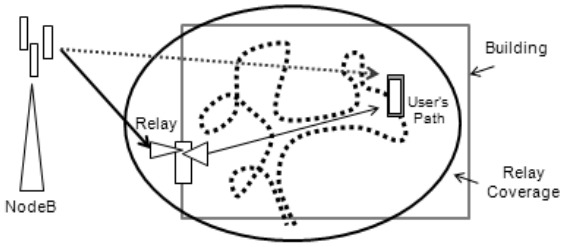


Figure 4. Collecting information on relay and macro coverage.

One of our design goals is for the existence of relays to be transparent to users and we seek to minimize network infrastructure impact. We assume a relay receives channel measurements from users within its coverage area (see Fig. 4), and in a margin of handover region beyond, and can thus determine EPLs. An expected density of users in relay coverage, or Relay Coverage Density (RCD), may be expressed in terms of a probability of a relay's user having a particular location with EPL *e*, or

$$RCD(e)=P\{EPL(u)=e\}. \quad (2)$$

For comparison with a macro base station, we define the Macro Penetration into Relay Coverage (MPRC), which can be

expressed as the distribution of the macro *m*'s receive signal code power reported by relay users (indicated by *u*), conditioned upon their reported EPL being *e*, or

$$MPRC(m,y,e)=P\{y(u,m)=y|EPL(u)=e\}. \quad (3)$$

Although both relay and macro power may be dynamic (e.g. due to load) the relay is assumed to know its own transmit power and we can determine a reference for the macro. For the latter, we are motivated to define Relay Coverage Effective Isolation (RCEI) as the distribution of difference Δy between a macro *m*'s measured receive code power at the relay's backhaul receiver $y(r,m)$ and that macro's receive code power reported by users $y(u,m)$ as a function of relay to user EPL *e*,

$$RCEI(m,\Delta y,e)=MPRC(m,\Delta y+y(r,m),e). \quad (4)$$

Using collected statistics for RCEI, the relay *r* can now compute, for any particular power *P* the relay may use, the expected association (serving cell) and signal-to-interference ratio (SIR) for any user *u* with EPL *e* as follows. The relay can determine the expected signal strength of its own signal $y(u,r)$ at the user *u* by subtracting the EPL *e* from the transmit power *P*. The relay can also determine the expected signal strength $y(u,m)$ of each macro cell *m* at the user by adding the relay's measurement of that macro strength $y(r,m)$ to the expected difference in power as compared to at the user, or $RCEI(m,\Delta y,e)$. Thus, SIR (in dB) can be approximated as,

$$\hat{SIR}(e) = E\{y(u,sc) - y(u,nsc) \mid \forall\, u, EPL(u)=e\}, \quad (5)$$

where *sc* denotes serving cell (whether the relay *r* or a macro *m*) and *nsc* represents non-serving cell(s). For simplicity, we may assume the serving cell is whichever is stronger at the user ($y(u,m)$ or $y(u,r)$) or bias either way (see below). Now, we can compute SIR with and without the relay present, or for any particular two relay power levels, and compare the SIR. For example, to compare expected capacity $\rho(e)$ for a given EPL *e* with equal serving time we can estimate SIR with (w/) and without (w/o) the relay for each active user's EPL *e*,

$$\rho(e) = log_2(1+ \hat{SIR}_{w/}(e)) - log_2(1+ \hat{SIR}_{w/o}(e)), \quad (6)$$

and average across users (assuming round robin or proportional fair scheduling). We may now also compute expected capacity ρ for a distribution of EPLs seen by relay users (in any particular range of EPLs),

$$\rho = \int RCD(e)\rho(e)de. \quad (7)$$

Thus, we have a method to collect statistics invariant with relay and macro power and compute optimal relay power for maximizing expected capacity. Adjustments to relay power (even to the extent of powering down completely) may be done in safe increments periodically.

III. Efficiency and Relay Mobility

A. The Backhaul Bottleneck Problem

Above, we considered an in-band (co-channel) relay (case III) and in determining relay power control we assumed unmodified association or serving cell selection methods. Moreover, if backhaul is a bottleneck, it is unlikely to be generally overcome by handover to a macro because access links and backhaul share a carrier (load). However, if we deploy a relay with a dedicated access link (case I) we may be motivated to maximize relay power. Now, if backhaul is a bottleneck it may be preferable to handover a user to a macro to move the link to a less loaded carrier (even if the relay access link appears higher quality to that user).

The long-term sustainable data rate *r* available to a user *u* when served by a relay is the minimum of the backhaul link rate r_{BHL} and relay access link rate r_{RAL} for the user,

$$r(u)=min(r_{BHL}(u),r_{RAL}(u)). \quad (8)$$

However, cellular mobility is typically determined by comparing pilot strength measurements M_u^{AL} for different cells' access links (AL) reported to the network by a user *u*. In particular, a user may trigger a report or handover when one access link pilot becomes better than another after factoring in biases β for the particular cells and a hysteresis value *H*,

$$M_u^{AL}(m)+\beta(m)+H \lessgtr^{?} M_u^{AL}(r)+\beta(r). \quad (9)$$

Without knowing backhaul quality, a user's comparison of access links may be insufficient for optimal handover decision. Only a relay and its hosting macro (NodeB) may directly measure the quality of the backhaul. Yet, for transparency, we seek to avoid modifications to NodeBs and legacy user terminals (so a relay appears to users as a regular NodeB).

Mobility is complicated by handover direction (see Fig. 5). A relay may have access to all relevant reports for determining whether to handover a user served by the relay to the hosting NodeB. However, this may not be the case if a user is served by a NodeB and would gain by handover to a relay.

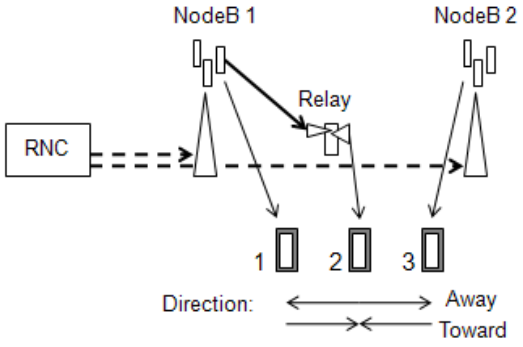


Figure 5. Handover direction may be toward or away from a relay.

If a user is served by a macro other than the macro hosting the relay, we might consider routing reports about backhaul (from relay) and access links (from user) to a decision making entity (Radio Network Controller (RNC) or relay) via different NodeBs. But timing is critical for handovers. Such separate reporting may result in non-optimal serving cell selection or ping-ponging, where a user is handed over in one direction only to be sent back.

Suppose a user terminal triggers handover events based on access links and a relay triggers handover for served users based on the backhaul link. These triggers may occur at different times (see Fig 6.). Thus, the RNC may not have timely (and correct) information to make handover decisions for the user because reports of the triggers generally occur at independent times. Ideally, handover decisions should be made on up to date information for all the relevant links or based on a comprehensive trigger (report).

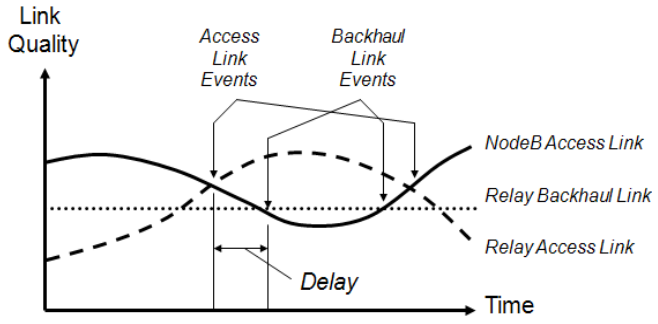


Figure 6. Asynchronous backhaul and access handover event reporting.

B. Relay Mobility Solution

To solve the above issues, we propose a simple solution. We propose that the relay r measures the backhaul (BHL) quality M_r^{BHL} for a hosting macro m and compares it to a threshold θ to compute a bias factor based on the specific BHL quality,

$$\Delta\beta = M_r^{BHL}(m) - \theta. \quad (10)$$

We specify the threshold based on the fraction of power allocated to pilot (e.g. 10% or -10dB). Thus, if backhaul is underused the bias will be positive and if the macro is at maximum power or there is significant interference (or both), the bias may be negative. A relay might perform such measurements and compute the bias on a regular basis (periodically) since load distribution may change significantly across day-time and night-time hours.

Furthermore, the relay communicates that bias directly to users served by the relay and/or to the RNC which conveys the bias to users served by macro NodeBs that are neighbors of the relay. These neighbors would typically be listed in the neighbor list for the user to search. Also, the bias may be added to any non-zero preconfigured cell individual offset (CIO) value that individual cells are assigned (e.g. by network management). The relay and RNC reuse an existing CIO protocol field to convey the new CIO values to users.

IV. System Simulation Results

A. System Simulation

We modeled relays and our algorithms in the context of a full downlink HSPA+ system simulation. We assume relays have directional antennas for backhaul and access links (70^o and 140^o half-power bandwidths (HPBW) respectively), with backhaul antenna pointed at the donor macro and access antenna pointed in the opposite direction for isolation purposes [7]. We model commercial and residential relays with maximum output powers of 30dBm and 10dBm respectively.

We modeled 7 site (21 cells) and 19 site (57 cells) scenarios with an Inter-Site Distance (ISD) of 1km. Our model comprises PedA 3km/hr fast-fading on access links and Rician (K=10) backhaul channels with propagation loss equations according to 3GPP standards and contributions for LTE-Advanced (LTE-A) [6, 7] which consider heights and line-of-sight (LoS) probabilities for relays versus macros. Scheduling is Proportional Fair (PF) or Equal Grade of Service (EGoS). A shadowing standard deviation of 8dB is consistent with experimental results [10]. Inter-site shadowing correlation is 0.5 (1.0 for cells at the same site) and a macro down-tilt of 10^o.

We generally model user distribution in the system as a combination of clustered and uniform (random) distributions with 16 dual-receive-antenna users per macro cell (i.e. 48 per NodeB), and 8 relays per cell. We assume 50% of users are clustered in uniformly distributed "hot-spots" each with a 50m radius. We deploy a relay at the edge of each cluster pointing into the cluster and generally assume all users (whether clustered or not) are indoors, introducing a normally distributed (N(20,20) in dB) penetration loss to coincide with experimentally observed indoor penetration losses.

In this paper, we use a 3GPP traffic model representing internet traffic: a Poisson burst model consisting of 1Mb pages with mean inter-arrival time of 5 seconds. We define user experience as the burst rate a user sees,

$$Burst\ Rate = Page\ Size / Page\ Delay \quad (11)$$

where *Page Delay* is the delay from first packet arriving in the NodeB queue to delivery of the last packet at the user.

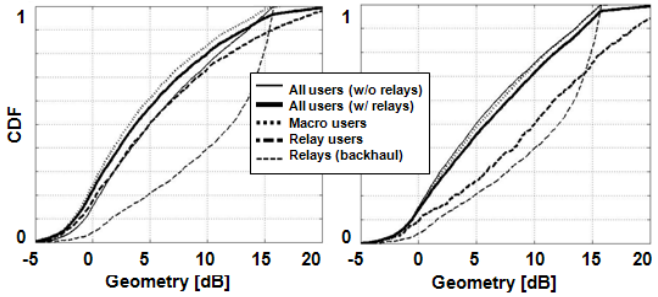
B. Results

To study the relay power control method, we focus on an in-band (co-channel) scenario (case III) since interference is at issue. Table I summarizes results with relay as compared to macro-only in three cases: (i) outdoor relay with both antennas outdoors; (ii) indoor relay with both antennas indoors; and (iii) hybrid arrangement with backhaul antenna outdoors and access antenna indoors. Without relay power control, a relay may use the maximum power (if fully loaded). We assume outdoor and hybrid relay deployments are commercial whereas indoor relays are residential. As expected, the hybrid relay offers the best performance because the backhaul antenna avoids penetration loss and the indoor access antenna causes less interference outside the coverage area.

TABLE I. RELAY POWER CONTROL BENEFITS IN CO-CHANNEL

Median Burst Rate Gains (5^{th} %-tile)	Outdoor Relay	Hybrid Relay	Indoor Relay
No Relay Power Control	32% (92%)	75% (128%)	35% (89%)
Relay Power Control	50% (95%)	88% (140%)	47% (101%)

We observe that relays offer particular benefits to weak coverage users (5^{th} percentile) but can provide modest capacity gain as well (median). Relay power control extends benefits more generally (affecting the median) because power control improves geometry not only of relay users but also macro users (see Fig. 7). According to equation (7) above, relays that would cause more interference to macro (and relay) users than benefit to relay (and macro) users (i.e. $\rho <= 0$) are powered down even though users that would have been served by that relay may be transferred back to macro service (see Table II) (we assumed each relay has all EPLs to compute the SIRs). Remarkably, even with most relays powered down, performance improves significantly.



(a) Without relay power control (b) With relay power control

Figure 7. Cumulative distribution function (CDF) of geometry (SIR) with and without relay power control broken down for macro and relay users.

The relay mobility method provides little or no further benefit to the relay power control method since power is determined assuming an unbiased association. An inconsistent bias may counter the assumption used in power optimization. However, if we dedicate a carrier for relay access link (case I) we may be motivated to maximize relay power. Yet, backhaul may be a bottleneck causing worse performance (in good macro coverage) than without relays, assuming we can operate macros in two carriers scheduling dual-carrier users in the two carriers to obtain a two-fold burst-rate gain by queuing theory (see Table III). Otherwise, depending on whether macro coverage is good (less penetration loss, 10dB for all users) or poor (more penetration loss, inducing about 10% outage) the relay mobility algorithm may be critical for gain (see Fig. 8).

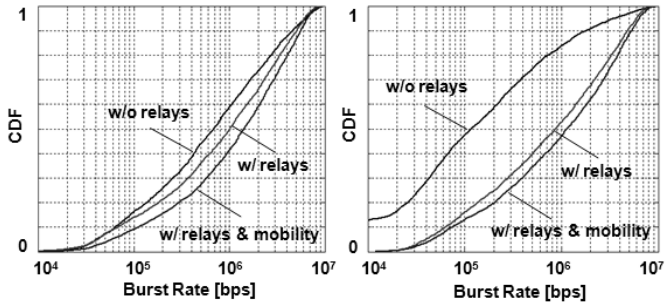
TABLE II. RELAY POWER CONTROL EFFECTS

Users Associated with Relays (% relays off[a])	Outdoor Relay	Hybrid Relay	Indoor Relay
No Relay Power Control	38% (0%)	44% (0%)	29% (0%)
Relay Power Control	19% (68%)	25% (27%)	18% (66%)

a. In these cases (uniform and cluster distribution) relay power control tends to cause near bimodal results (i.e. relays either at full power or off/idle).

TABLE III. RELAY MOBILITY BENEFITS IN DEDICATED ACCESS LINK

Median Burst Rate Gains (10^{th} %-tile)	Good Coverage	Poor Coverage
No Relay Mobility	-28% (-45%)	280% (~200%)
Relay Mobility	+4% (-13%)	380% (~250%)



(a) Good coverage (b) Poor coverage

Figure 8. Cumulative distribution function (CDF) of burst rate performance with and without relay mobility bias to account for backhaul quality (without multi-carrier queuing gain assumption for w/o relay baseline).

V. CONCLUSION

Dynamic relay power control may be both economical and important for performance when relay links share resources. Remarkably, better performance may be achieved with less users associating to relays and may indirectly take into account backhaul constraints affecting optimal handover. In contrast, consideration of backhaul in determination of mobility (association) may be critical to achieving gain when dedicated resources are allocated for relays.

REFERENCES

[1] R. Imrer and F. Diehm, "On Coverage and Capacity of Relaying in LTE-Advanced in Example Deployments", *IEEE PIMRC*, 2008, pp. 1-5.

[2] T. Beniero, S. Redana, J. Jamalainen, and B. Raaf, "Effect of relaying on coverage in 3GPP LTE-advanced," *IEEE VTC*, Spring, 2009.

[3] E. K. Tameh, A. Nix, and A. Molina, "The Use of Intelligently Deployed Fixed Relays to Improve the Performance of a UTRA-TDD system", *IEEE VTC*, Fall 2003, pp. 1890-1894.

[4] K. Georgiev and D.C. Dimitrova, "Impact of relaying on inter-cell interference in mobile cellular networks", *European Wireless Conference*, 2010.

[5] H. Holma and A. Toskala, *WCDMA for UMTS – HSPA Evolution and LTE*, 4^{th} Ed., Wiley, 2007.

[6] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. You, O. Song, and D. Malladi, "A Survey on 3GPP Heterogeneous Networks", IEEE Wireless Communications, June 2011.

[7] A. S. M. Marzuki, A. R. A. Rahim, B. Mohmd, K. Khalil, A. Naemat, and A. Tee, "Antenna Isolation Considerations in WCDMA Repeater Deployment", *IEEE RF and Microwave Conference*, 2006, pp 347-350.

[8] 3gpp LTE-Advanced TSG-RAN WG1 #54-bis, R1-084026, "Text Proposal for Evaluation Methodology", Sept 29-Oct 3, 2008.

[9] 3gpp LTE-Advanced TR 36.814 "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects", (Release 9), March 30^{th}, 2010.

[10] P.E. Mogensen, P. Eggers, C. Jensen, and J.B. Andersen, "Urban Area Radio Propagation Measurements at 955 and 1845 MHz for Small and Micro Cells", *IEEE Globecom*, 1991, pp 1297-1302.