Abstract—This paper studies the problem of scheduling, precoding and limited feedback design for the emerging 3GPP-LTE systems over time- and frequency-selective (doubly selective) channels. In particular, greedy scheduling with zero-forcing (ZF) precoding is considered for the doubly selective multiuser multiple-input single-output (MISO) orthogonal frequency division multiplexing (OFDM) downlink channels. In limited feedback design, the discrete prolate spheroidal basis expansion model (DPS-BEM) is used as a fitting parametric model for capturing the time-variation of the doubly selective channels and reducing the number of the channel parameters. The resulting dimension reduction in the channel representation, in turn, translates into a reduced feedback load of channel state information (CSI). To exploit the considerable reduction in CSI feedback load, vector quantization (VQ) of DPS-BEM parameters is performed at users’ receivers under the assumption that perfect BEM parameter estimation has been established by existing algorithms. The output indices of the quantized BEM parameter vectors are, then, sent to the base station (BS) via error-free limited feedback links. With the channel state information (CSI) at transmitter (CSIT), greedy scheduling and ZF precoding are deployed for multiuser transmission in each subcarrier of OFDM symbols in a LTE frame. Numerical results show that the ZF-based multiuser transmission scheme with the suggested BEM quantization and limited feedback design offers significant sum-rate gains and stable performance with high robustness against time-varying channels.

Index Terms—Scheduling, precoding, limited feedback, vector quantization, discrete prolate spheroidal basis expansion model (DPS-BEM), time- and frequency-selective channels.

I. INTRODUCTION

The integration of multi-antenna and orthogonal frequency division multiplexing (OFDM) techniques has provided remarkable diversity and capacity gains in broadband wireless communications ranging from single-user to multiuser (MU) systems [1]. Especially, in MU transmissions, the use of multi-antenna array at the base station (BS) enables simultaneous transmission of multiple data streams to multiple users by exploiting spatial separations among users. In the so-called spatial division multiple access (SDMA), multiuser diversity is the primary factor that increases significantly the system sum-rate [3]. As a result, an appropriate multiuser encoding technique (at the BS) is indispensable to attain the considerable sum-rate gain in SDMA. It is well-known that dirty paper coding (DPC) [2] is an optimal multiuser encoding strategy that achieves the capacity limit of MU broadcast (BC) channels [5] but at the cost of extremely high computation burden as the number of users is large. Recent studies have introduced several suboptimal multiuser encoding techniques with lower complexity (relative to DPC) that can be categorized into nonlinear (i.e., vector perturbation [9], Tomlinson Harashima precoding [8]) and linear precoding (e.g., minimum mean squared error (MMSE) [7], zero-forcing [3]).

With a much lower complexity than non-linear precoding, linear precoding (or beamforming) techniques are still able to approach asymptotically (as the number of users is large) the capacity limit of the BC channel [6]. In beamforming (BF)-based multiuser transmissions, each user’s coded data stream is pre-multiplied by a weighting vector before being fed to transmit antennas. By exploiting spatial separations among users (based on the use of CSIT), appropriate weighting vectors can be computed to eliminate inter-user interference and enable reliable multiuser transmissions. Determining the optimal weighting vectors, unfortunately, leads to a difficult nonconvex optimization problem [3]. As a very simple, but efficient, solution to the problem of finding the BF weighting vectors, zero-forcing (ZF) precoding using perfect channel state information (CSI) is able to provide a sum-rate performance which is quite close to that of DPC [3] in a large user pool. In adaptive transmissions (non-linear/linear precoding), acquiring perfect CSI at BS via full (analog) feedback could, however, be an infeasible task in some wireless communications systems, specially in those over time-varying channels, due to a possibly large CSI feedback load and outdated CSI feedback. To overcome this challenge, limited (or finite-rate) feedback of CSI [11] has been considered in the literature and industry as well. Recent studies have shown that limited feedback of a small number of bits about the channel characteristics can provide a near-optimal system performance [11].

Most of existing precoding/scheduling techniques assume wireless channels to be time-invariant within a transmission frame/burst. However, in MU networks with rapidly moving nodes (i.e., users in cars and trains in LTE systems), the resulting time-variation (time-selectivity) of the channel impulse response (CIR) introduces a large number of channel parameters, leading to a very high CSI feedback load.
for precoding/scheduling (with consideration of time-varying channels). In addition, the presence of time-varying channels also gives rise to the problem of outdated CSI feedback that could severely degrade the system performance. To deal with the channels, [10] has proposed a MMSE-based beamforming algorithm over spatially correlated, frequency-flat, time-varying channels. Specifically, the existing technique uses full feedback of channel distribution information (CDI) and an iterative beamforming process to provide stable multiuser transmissions over the channels.

Unlike [10], this paper considers limited feedback of CIR using basis expansion model (BEM) quantization for ZF precoding and greedy scheduling over spatially uncorrelated, time- and frequency-selective (doubly selective) channels. In particular, for limited feedback design over the doubly selective channels, the discrete prolate spheroidal basis expansion model (DPS-BEM) [13] is used as a fitting parametric model for capturing the time-variation of the channels (generated by the modified Jakes’ method [16]) and reducing the number of the channel parameters. The resulting dimension reduction in the channel representation, in turn, translates into reduced feedback load of CSI. To obtain the considerable reduction in CSI feedback load, vector quantization (VQ) of DPS-BEM parameters is performed at users’ receivers under the assumption that perfect BEM parameter estimation has been established by existing algorithms [12], [13]. The output indices of the quantized BEM parameter vectors are, then, sent to the base station (BS) via error-free limited feedback links. With the channel state information (CSI) at transmitter (CSIT), greedy scheduling and ZF precoding are deployed for multiuser transmission in each subcarrier of OFDM symbols in a LTE frame.

The rest of the manuscript is organized as follows. Section II delineates the system and channel models. The suggested DPS-BEM quantization and limited feedback for ZF precoding and greedy scheduling are presented in Section III. Simulation results and relevant discussions are located in Section IV. Finally, Section V provides some concluding remarks.

Notations: The uppercase and lowercase boldface letters are used for matrices and vectors, respectively. $(X)^*$ denotes the conjugate transpose (Hermitian operator) of the matrix $X$. $\mathcal{E}(.)$ stands for expectation operator.

II. SYSTEM FORMULATION

A. Transmitted Signal Model

Consider a (homogeneous) multiuser multiple-input single-output (MISO) LTE downlink channel where the base station is equipped with $N_t$ transmit antennas and each user possesses a single receive antenna. Orthogonal frequency division multiplexing (OFDM) modulation and $N$-point fast Fourier transform (FFT) are employed for the downlink multi-carrier transmission. After inverse FFT (IFFT), cyclic prefix (CP) insertion and digital-to-analog conversion (DAC), the transmitted baseband signal of the $u$th transmit antennas can be written as

$$x_n^{(u)} = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_{k,m}^{(u)} \exp \left( \frac{j2\pi kn}{N} \right)$$

where $n \in \{-N_g, \ldots, 0, \ldots, N-1\}$, $N_g$ denotes the CP length, $X_{k,m}^{(u)}$ is the $k$th data-modulated/precoded subcarrier in the $m$th OFDM symbol from the $u$th transmit antenna. It is noted that $X_{k,m}^{(u)}$ is the superposition of selected/scheduled users’ precoded subcarriers in multiuser transmissions.

The transmitted baseband signal $x_n^{(v)}$ in (1), then, undergoes a doubly selective multiuser MISO channel as mathematically described in the next subsections.

B. Doubly Selective Channel Model

In the study, for each pair of the $u$th transmit antenna (at BS) and the $v$th user’s receive antenna, the time-varying channel response that includes the effect of transmit-receive filters and doubly selective propagation is denoted by $h_{l,n,m}^{(v,u)}(t, \tau)$. In the considered LTE system [14], the DPS-BEM [13] is employed for capturing the time-variation of the channel. With the aid of DPS-BEM, the time-varying channel tap gain of the $l$th resolvable path between the $u$th transmit antenna and the $v$th user’s receive antenna at the $n$th time instance in the $m$th OFDM symbol can be represented as

$$h_{l,n,m}^{(v,u)} = \sum_{q=1}^{Q} b_{n+mN_s,q} c_{q,l}^{(v,u)} , l \in \{0, \ldots, L-1\}$$

where the mobile users’ speed can be assumed to be time-invariant within $M$ OFDM symbols in a duration of a few LTE frames. $L$ denotes the channel length, $b_{n+mN_s,q}$ stand for the corresponding basis function values of the time-varying channel and $N_s = N + N_g$ denotes the OFDM symbol length after CP insertion. $c_{q,l}^{(v,u)}$ are the DPS-BEM parameters of the channel. $Q$ is the number of basis functions used in the DPS-BEM.

C. Received Signal Model

Over the above time-varying multipath downlink channels, after CP removal, the $n$th received sample in the $m$th OFDM symbol at the $v$th user’s received antenna, $y_{n,m}^{(v)}$, can be represented by

$$y_{n,m}^{(v)} = \sum_{u=1}^{N_t} \sum_{l=0}^{L-1} h_{l,n,m}^{(v,u)} x_{n-l,m}^{(u)} + z_{n,m}^{(v)} , n \in \{0, \ldots, N-1\}$$

where $z_{n,m}^{(v)}$ is the additive white Gaussian noise (AWGN) with unit variance $N_0 = 1$ (after normalization) at the $v$th user.

After FFT at users, the $k$th subcarrier in the $m$th OFDM symbol at the $v$th user’s receive antenna can be determined by

$$Y_{k,m}^{(v)} = \sum_{u=1}^{N_t} H_{k,k,m}^{(v,u)} X_{k,m}^{(u)} + I_{k,m}^{(v)} + Z_{k,m}^{(v)}$$

where $I_{k,m}^{(v)} = \sum_{u=1}^{N_t} \sum_{i=0}^{N-1} H_{k,i,m}^{(v,u)} X_{i,m}^{(u)}$ is the inter-carrier interference (ICI) induced by the time-varying channel. $H_{k,i,m}^{(v,u)} =$
For the sake of notational simplicity, the OFDM symbol index \( m \) can be omitted the subsequent formulations. As a result, the \( k \)th received subcarrier of the \( r \)th user can be represented by

\[
Y_r^{(v)} = H^{(v)}_{k,r} X_k + Z_r^{(v)},
\]

where \( H^{(v)}_{k,r} = \left[H^{(v,1)}_{k,k}, \cdots, H^{(v,N_r)}_{k,k}ight] \) and \( X_k = \left[X^{(1)}_{k,1}, \cdots, X^{(N_r)}_{k,1}\right]^T \). It is assumed that the base station has an average transmit power constraint \( \text{trace}(E [X_k X_k^H]) \leq P \).

In this paper and other existing precoding/scheduling studies \([10]\) as well, the ICI can be negligible in (5) since its power is much smaller than that of the subcarrier of interest under the current LTE system parameters \([14]\). This can be verified by numerical results as shown in Fig. 1. In particular, given an index of subcarrier of interest \( k \), the figure shows the squared amplitude values of \( H^{(v,u)}_{k,i,m} \) versus interfering subcarrier’s index \( i \). As can be seen, given \( k = 10 \), the curve value at \( i = 11 \) (power of the nearest neighboring interfering subcarrier) is about 30dB smaller than that at \( i = k = 10 \) (the power of the subcarrier of interest) at the mobile user speed of 400km/h.

III. PRECODING AND SCHEDULING WITH BEM-BASED LIMITED FEEDBACK

A. Zero-Forcing Precoding

In ZF beamforming (BF) techniques \([3]\), the inter-user interference in (5) can be eliminated by pre-multiplying users’ data subcarrier streams with weighting vectors. Specifically, let \( s^{(v)}_k, w^{(v)}_k = [w^{(v)}_{k,1}, \cdots, w^{(v)}_{k,N_r}]^T \) and \( P^{(v)}_k \) be the data symbol, BF weighting vector, and transmit power scaling factor of the \( k \)th subcarrier of the \( v \)th user, respectively. For a set of \( V \) (selected/scheduled) users, the transmitted signal at BS is

\[
X_k = \sum_{v=1}^{V} w^{(v)}_k \sqrt{P^{(v)}_k} s^{(v)}_k = W_k S_k
\]

where \( W_k = \left[w^{(1)}_k, \cdots, w^{(V)}_k\right]^T \), \( S_k = \left[\sqrt{P^{(1)}_k} s^{(1)}_k, \cdots, \sqrt{P^{(V)}_k} s^{(V)}_k\right]^T \) and \( E \left[\left(s^{(v)}_k\right)^2\right] = 1 \).

Using (5), the received signals of \( V \) selected/scheduled users can be represented in a vector form as

\[
Y_k = H_k W_k S_k + Z_k
\]

where \( H_k = \left[H^{(1)}_{k}, \cdots, H^{(V)}_{k}\right]^T \), \( Y_k = [Y^{(1)}_k, \cdots, Y^{(V)}_k]^T \) and \( Z_k = [Z^{(1)}_k, \cdots, Z^{(V)}_k]^T \).

In zero-forcing beamforming (ZFBF), the matrix of weighting vectors \( W_k \) is computed to eliminate the inter-user interference in (7). As a result, a simple solution of \( W_k \) is the pseudoinverse of \( H_k \)

\[
W_k = H_k^* (H_k H_k^*)^{-1}.
\]

By plugging (8) into (7), the resulting received signals at selected users after ZF precoding will be

\[
Y_k = S_k + Z_k.
\]

Over the channel having receiver noise with unit variance \((N_0 = 1)\), the resulting sum-rate at the \( k \)th subcarrier of the considered system can be determined by

\[
R_k = \max_{v \in \Omega} \sum_{v \in \Omega} \log \left( 1 + P^{(v)}_k \right)
\]

where \( \lambda^{(v)}_k = \left[(H_k H_k^*)^{-1}\right]_{v,v} \) and \( \Omega \) denotes the set of selected/scheduled users.

The optimal power allocation \( P^{(v)}_k, v \in \{1, ..., V\} \) in (10) can be easily determined by the following waterfilling process

\[
P^{(v)}_k = \left(\mu / \lambda^{(v)}_k - 1\right)^+.
\]

where \( x^+ \) denotes \( \max(x, 0) \), and the water level \( \mu \) is chosen to satisfy

\[
\sum_{v \in \Omega} \left(\mu - \lambda^{(v)}_k\right)^+ = P.
\]

Given a set of selected users, the above precoding process attempts to eliminate the inter-user interference and maximize the system sum-rate. The problem of how to perform user selection (finding the set \( \Omega \)) with a reasonable complexity for maximizing the system sum-rate will be addressed in the next subsection.
B. Greedy Scheduling

Given a precoding technique, scheduling (user selection) is to find a set of users among all active users to maximize the system sum-rate. Obviously, the simple optimal method for user selection is exhaustive search but its complexity is impractically high as the number of users is large. To avoid the impractical implementation, greedy scheduling is considered in the paper. With the aforementioned ZF precoding technique, the detailed implementation of the greedy scheduling for a system with $N_u$ available users can be described in the following steps:

1) Initialization: $\Theta_0 = \{1,2,\ldots, N_u\}$ is the set of all available users’ indices. $\Omega_0 = \{\emptyset\}$ is the set of selected users, initially assigned to a null set, $\eta = 0$ stands for the number of selected users, initially set to zero. $R_0 = 0$ is the system sum-rate of selected users, initially set to zero.

2) Repetition: Assuming that selecting user $v$ in the set $\Theta_\eta$ results in the maximum sum-rate, called $C_{\text{max}}$.

- $\eta = \eta + 1$
- If $C_{\text{max}} < R_{\eta-1}$ or $\eta > N_\ell$ or $\eta > N_u$ go to Step 3 otherwise do:
  - $R_\eta = C_{\text{max}}$
  - $\Omega_\eta = \Omega_{\eta-1} \cup \{v\}$ (select one more user)
  - $\Theta_\eta = \Theta_{\eta-1} \setminus \{v\}$
- Go to Step 2.

3) Stop the user selection process and compute the ZF weighting vectors based on the composite channel matrix of selected users as presented in (8).

As aforementioned, precoding and scheduling in multiuser transmissions have to make use of CSIT via either full or limited feedback links. Unlike [3] and [10] considering full feedback of CSI, this paper uses limited feedback with BEM vector quantization for precoding and scheduling as presented in the next section.

C. BEM Quantization and Limited Feedback Design

In adaptive transmission (non-linear/linear precoding), obtaining perfect CSI at BS via full feedback links could, however, be an impractical task in some wireless communication systems, specially in those over time-varying channels since the resulting CSI feedback load can be extremely large. To deal with this problem, limited (or finite-rate) feedback of CSI has been considered in the literature and industry as well. Recent studies have shown that limited feedback of a small number of bits about the channel characteristics can provide near-optimal system performance [11].

In particular, for limited feedback design over time- and frequency-selective (doubly selective) channels, the discrete prolate spheroidal basis expansion model (DPS-BEM) [13] is used as a fitting parametric model of the doubly selective channels. The use of DPS-BEM helps to reduce dramatically the number of time-varying channel parameters. For instance, in the current LTE system settings [14], one LTE frame contains 140 OFDM symbols with 128-FFT (the smallest FFT size used in the LTE settings) and the resulting number of the time-varying channel parameters corresponding to one channel tap gain $h_{i,n,m}^{(v,u)}$ in (2) will be $140 \times 128 = 17,920$. By using the DPS-BEM as shown in (2), the number of the fitting model parameters $Q$ can vary from 10 (for a moderate user speed, e.g., about $100\text{km/h}$) to 40 (for a high user speed, e.g., about $400\text{km/h}$). In other words, using the DPS-BEM in the current LTE system settings reduces the number of the channel parameters about 450 times. This, obviously, leads to a considerable reduction in CSI feedback load to the BS.

In this paper, it is assumed that the perfect BEM parameter $c_{q,i}^{(v,u)}$ estimation at users has been established (by existing algorithms [12], [13]) then vector quantization of the resulting BEM parameter estimates is performed by using the predetermined Linde-Buzo-Gray (LBG) codebook [4]. In particular, the codebook, that takes into consideration the BEM parameter distributions, is pre-generated by the LBG algorithm [4] using 1E5 training vectors of BEM parameters. Then, the indices of the quantized vectors of the BEM parameters are sent to the BS via error-free limited feedback links. Based on the knowledge of the feedback indices, the BS is able to determine the channel responses of all BS-to-user links that will be used in the precoding and scheduling processes as described in subsections III.A and III.B.

IV. SIMULATION RESULTS AND DISCUSSIONS

In the simulated LTE system, the time-varying multipath ($L = 5$) channels with exponentially decaying power-delay profile [13], [15] are first generated by the modified Jakes’ technique [16], and then fitted (approximated) by the DPS-BEM [13]. Unless otherwise stated, there are ten available users ($N_u = 10$) in the LTE system where the BS is equipped with four transmit antennas ($N_\ell = 4$), and the DPS-BEM uses 40 BEM parameters ($Q = 40$) to represent one time-varying channel tap gain in (2) with mobile user speeds up to 400 km/h. For vector quantization of DPS-BEM parameters $c_{q,i}^{(v,u)}$ at users, a vector of the 40 BEM parameters is first partitioned into 20 subvectors of 2 BEM parameters (doing the partition helps to reduce the size of a predetermined codebook as mentioned later). Then, each of these subvectors (of 2 BEM parameters) is quantized by the LBG codebook [4]. The codebooks, known to both the BS and users, are pre-generated by using the LBG algorithm [4] with 1E5 training vectors of BEM parameters. After the vector quantization of all 20 subvectors, binary bits representing the indices of the quantized subvectors are sent to the BS via error-free feedback links. Based on the indices, the BS can determine the time-varying channel responses for the ZF precoding and scheduling at each subcarrier of each OFDM symbols in a LTE frame. Following the 3GPP-LTE settings [14], in the simulated system, one LTE frame consists of 20 time slots and each of these contains 7 OFDM symbols (140 OFDM symbols in one LTE frame). In addition, 128-point FFT with sampling frequency $f_s = 1.92\text{MHz}$ and carrier frequency $f_c = 2\text{GHz}$ is used for the simulated multicarrier transmissions. The CP length of each OFDM symbol is set to 10 samples [14].
The average transmit power constraint is $P = 10$. In the figures illustrating the simulation results, each plotted point of the sum-rate performance is obtained by averaging over 300 independent channel realizations.

Fig. 2 shows the sum-rate performance of the ZF precoding with greedy scheduling using: i) full feedback of \textit{perfect} time-variant CSI (Curve B), ii) the suggested BEM quantization and limited feedback (Curve C), and iii) full feedback of perfect CSI (Curve D) but ignoring the effect of time-varying channels (assuming the channels to be time-invariant in one LTE frame) versus different numbers of users. For comparison, the asymptotic (in a large user pool) sum-rate performance of DPC (Curve A) is also plotted. As shown in [3], the asymptotic sum-rate is determined by $E(R_{DPC}) = N_t \log(1 + P \log N_u / N_t)$. As observed in Fig. 2, the suggested BEM quantization and limited feedback scheme (Curve C) offers a significant sum-rate gain relative to the case of using full feedback of perfect CSI but ignoring the effect of time-varying channels (Curve D). Furthermore, the sum-rate performance of the BEM quantization and limited feedback scheme is very close to that of the ideal case where the BS uses \textit{full} feedback of \textit{perfect} time-variant CSI (Curve B). As can be seen from Curve D, over time-varying channels, i.e., in LTE systems with high-speed mobile users, the detrimental effect of \textit{outdated} CSI feedback incurs a considerable sum-rate loss as using the assumption of block fading channels (assuming the channel to be time-invariant in one LTE frame) in precoding and scheduling.

Fig. 3 presents the sum-rate performance of the ZF precoding/scheduling using the following CSI feedback schemes: i) full feedback of \textit{perfect} time-variant CSI (Curve A), ii) the suggested BEM quantization and limited feedback (Curve B), and iii) full feedback of perfect CSI but ignoring the effect of time-varying channels (Curve C) versus different numbers of feedback bits, $N_{FB}$, for each quantized subvector of 2 BEM parameters. It is noted that the total number of feedback bits for one time-varying channel tap gain is $(40/2)N_{FB} = 20N_{FB}$ (under the use of 40 BEM parameters for a mobile user speed of 400 km/h). As observed in Curve B, with a predetermined LBG codebook’s cardinality of more than $2^7$ ($N_{FB} = 7$bits), the sum-rates of the suggested BEM quantization and limited feedback scheme are comparable to that of the ideal case where the BS uses \textit{full} feedback of \textit{perfect} time-variant CSI. As can be seen in Curve B, the BEM quantization and limited feedback with only $N_{FB} = 3$bits can provide a better sum-rate performance than the case of using full feedback of perfect CSI but ignoring the effect of time-varying channels (Curve C).

In Fig. 4, the sum-rate performance under the various CSI feedback schemes versus different mobile user speeds is plotted. Specifically, the plotted results are under the following cases: i) using full feedback of \textit{perfect} time-variant CSI (Curve A), ii) using the suggested BEM quantization and limited feedback (Curve B), and iii) using full feedback of \textit{perfect} CSI but ignoring the effect of time-varying channels (Curve C). As can be seen, the use of the BEM quantization and limited feedback (Curve B) provides a stable sum-rate performance with high robustness against time-varying channels while \textit{full} feedback of \textit{perfect} CSI but without the consideration of the time-varying channel effect (Curve C) incurs a significant sum-rate loss (due to the detrimental effect of \textit{outdated} CSI feedback) as the mobile user speeds are higher than 25km/h.

Fig. 5 shows the sum-rate performance under various CSI feedback cases versus different numbers of DPS-BEM bases used for fitting the time-varying channels with a mobile user speed of 100 km/h. In particular, we consider the following CSI feedback schemes: i) using full feedback of \textit{perfect} time-variant CSI (Curve A), ii) using the suggested BEM quantization and limited feedback (Curve B), and iii) using full
As can be observed, using just 10 DPS-BEM bases to capture the channel’s time-variation, the LTE systems over doubly selective channels. By employing coding with limited feedback design for the emerging 3GPP-perfect time-variant CSI (Curve A). very close to that of the ideal case of using full feedback of feedback scheme (Curve B) to provide sum-rate performance scheduling with the suggested BEM quantization and limited feedback helps to avoid the detrimental effect of outdated CSI feedback and provides stable sum-rate performance in multiuser transmissions with a wide range of mobile user speeds.

V. Conclusion

The paper investigates the problem of scheduling and precoding with limited feedback design for the emerging 3GPP-LTE systems over doubly selective channels. By employing the DPS-BEM to capture the channel’s time-variation, the resulting feedback load of BEM parameters is significantly smaller than that of channel impulse response (CIR) or channel frequency response (CFR). Over time-varying channels, the suggested BEM quantization and limited feedback helps to avoid the detrimental effect of outdated CSI feedback and provides stable sum-rate performance in multiuser transmissions with a wide range of mobile user speeds.

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REFERENCES