

Doppler Shift in LEO Direct-to-Cell Satellite Links Serving High-Mobility Users: Characterization, Residual-Offset Budget, and Beam-Sizing Limits

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Doppler Shift in LEO Direct-to-Cell Satellite Links Serving High-Mobility Users: Characterization, Residual-Offset Budget, and Beam-Sizing Limits

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Abstract—Direct-to-Cell (D2C) satellite service connects unmodified LTE/5G smartphones to low-Earth-orbit (LEO) satellites that carry an on-board base station. Because the satellite moves at about 7.6 km/s and the handset may itself be travelling in a car, a high-speed train or an aircraft, the link is exposed to large and rapidly varying Doppler shifts. This paper develops a unified kinematic model of the D2C service link that combines satellite orbital motion with arbitrary user-equipment (UE) velocity, and uses it to quantify (i) the raw Doppler shift and Doppler rate for altitudes of 360–600 km in the 1.9–2.0 GHz band, (ii) the residual frequency offset that remains after beam-centre Doppler pre-/post-compensation, and (iii) the resulting uplink round-trip offset, which is shown to be twice the downlink residual for legacy handsets that lock their oscillator to the received downlink. At 360 km and 1.99 GHz the raw Doppler reaches ± 47.6 kHz with a peak rate of 1034 Hz/s. A counter-moving vehicle raises the relative speed by at most 3.6% even at 1000 km/h, so its effect on the raw Doppler is minor; after compensation, however, the vehicle term becomes a first-order contributor, reaching 1239 Hz on the uplink for a 350 km/h train and 3.54 kHz for an aircraft. Closed-form expressions are derived for the residual-Doppler gradient and for the maximum beam radius that keeps the uplink offset within the PRACH restricted-set limits, and they are validated by Monte-Carlo simulation. The results show that low-elevation beams are vehicle-limited whereas near-nadir beams are geometry-limited, and that airborne users cannot be served by legacy handsets at elevations below about 45° without additional compensation.

Index Terms—Direct-to-cell, direct-to-device, Doppler shift, LEO satellite, non-terrestrial networks (NTN), high-mobility, carrier frequency offset, inter-carrier interference, LTE, 3GPP.

I. INTRODUCTION

Satellite-based extension of terrestrial cellular coverage has moved from concept to commercial service in only a few years. Non-terrestrial networks (NTN) are now an integral part of the 5G and 6G roadmaps [1], [2], and 3GPP has standardized NR and IoT operation over satellites from Release 17 onwards [3]. In parallel, operators have deployed *Direct-to-Cell* (D2C), also called direct-to-device, systems that connect *unmodified* LTE smartphones directly to LEO satellites. SpaceX’s Starlink D2C service flies an LTE eNodeB on each satellite and operates in terrestrial PCS spectrum (LTE Band 25, 1910–1915 MHz uplink and 1990–1995 MHz downlink in the U.S.) [4], [5]; its second-generation D2C satellites are authorized at 340–360 km altitude [6]. AST SpaceMobile’s BlueBird Block 2 satellites operate at about 520 km with very large phased-array apertures [7].

Low altitudes are attractive for link budget and latency, but they maximize the satellite’s orbital velocity relative to the ground and therefore the Doppler shift. For a LEO satellite at 600 km in the S-band, 3GPP reports Doppler shifts of up to ± 48 kHz (24 ppm) and Doppler-rate magnitudes of about 544 Hz/s [8], [9]. These values exceed by orders of magnitude the offsets

a terrestrial LTE receiver is designed for. Release-17 NTN handsets solve this autonomously by computing the service-link Doppler from their own GNSS position and the broadcast satellite ephemeris and pre-compensating their uplink [10]. Legacy LTE phones, which are the very target of commercial D2C service, have no such capability. The network must therefore pre-compensate the downlink and post-compensate the uplink with respect to a reference point, typically the beam centre, and the handset must tolerate whatever residual offset remains.

A second, less studied factor is the mobility of the handset itself. Users increasingly expect connectivity on highways, on high-speed rail (HSR) lines operating at 300–350 km/h, and on-board aircraft cruising near 900–1000 km/h. A common intuition is that a vehicle moving opposite to the satellite adds its speed to the satellite’s, producing a very large resultant velocity and Doppler shift. This paper examines that intuition quantitatively. We show that the vehicle’s contribution is small relative to the raw satellite Doppler but becomes a dominant term once the satellite Doppler has been compensated, precisely because it is user-specific and cannot be removed by beam-level compensation.

The main contributions of this paper are as follows:

- A unified vector model of the D2C service-link Doppler that combines circular-orbit satellite motion with arbitrary UE velocity, with closed-form expressions for Doppler shift and rate validated against 3GPP reference values.
- A derivation of the **round-trip** residual offset for legacy handsets under beam-centre compensation, showing that the uplink offset seen by the satellite is twice the downlink residual plus the UE oscillator error.
- A closed-form approximation of the residual-Doppler gradient across a beam and a resulting design rule for the maximum beam radius as a function of altitude, elevation and vehicle speed, checked against exact numerical evaluation.
- A Monte-Carlo characterization of the uplink offset distribution for static, road, HSR and in-flight user populations, together with an inter-carrier interference (ICI) assessment and a discussion of mitigation options.

The rest of the paper is organized as follows. Section II reviews work related and the relevant standards. Section III presents the system model and derivations. Section IV describes the simulation methodology. Section V presents and discusses the results, and Section VI concludes the paper.

II. BACKGROUND AND RELATED WORK

A. Doppler in LEO Satellite Links

The classical analytic characterization of LEO Doppler is due to Ali *et al.* [11], who derived the Doppler shift and its rate as a function of time for a terminal on a rotating Earth and used it for visibility prediction and Doppler-based access [12]. Survey articles on satellite integration into 5G identify Doppler and its time variation as one of the key physical-layer challenges for LEO systems [1], [13]. 3GPP TR 38.811 [8] and TR 38.821 [9] provide the reference figures most often quoted: up to ± 48 kHz at 2 GHz and 600 km, and a maximum variation of -544 Hz/s, observed at the instant the Doppler crosses zero. For IoT NTN, TR 36.763 lists a maximum Doppler of 24 ppm and a variation of 0.27 ppm/s for an Earth-fixed device at 600 km [14].

B. Doppler Compensation Strategies

Two broad strategies exist. In UE-side compensation, standardized in Release 17, a GNSS-equipped NTN UE computes the Doppler of its own service link and pre-compensates its uplink, while the network handles the feeder link [10]. In network-side compensation, the satellite or ground segment pre-compensates the downlink and post-compensates the uplink for a reference point, usually the beam centre, so that only a *differential* Doppler remains for users elsewhere in the beam. Meshram *et al.* analysed beam-centric pre-compensation for regenerative 5G NTN and its effect on initial synchronization [15]. Tanash *et al.* recently used stochastic geometry to show that the geometry-induced residual Doppler after common compensation still causes significant ICI and coverage loss in OFDMA LEO systems [16]. These works, however, consider static or slowly moving users.

C. High-Speed Terrestrial LTE

Terrestrial LTE addressed vehicle-induced Doppler for HSR. The physical random-access channel (PRACH) uses Zadoff–Chu preambles whose cyclic-shift detection is corrupted by frequency offsets; LTE therefore defines *restricted sets* of cyclic shifts that tolerate offsets up to one PRACH subcarrier spacing (1.25 kHz) [17], and Release 14 added a second restricted set that tolerates up to twice that, ± 2.5 kHz, for very-high-speed cells [18]. LTE UEs must also keep their transmit frequency within ± 0.1 ppm of the received downlink carrier [19]. In this paper the 1.25 kHz and 2.5 kHz limits are used as conservative design thresholds for the residual uplink offset.

To the best of the authors' knowledge, no prior work jointly quantifies satellite and vehicle Doppler for legacy-handset D2C links, accounts for the uplink round-trip doubling, and translates the result into beam-size limits for concrete D2C altitudes and bands.

III. SYSTEM MODEL

A. Orbital Kinematics

We consider a satellite on a circular orbit of altitude h above a spherical Earth of radius $R_E = 6371$ km. With the gravitational parameter $\mu = 3.986 \times 10^{14} \text{ m}^3/\text{s}^2$, the orbital speed and angular rate are [20]

$$v_s = \sqrt{\frac{\mu}{R_E + h}}, \quad \omega_s = \frac{v_s}{R_E + h} \quad (1)$$

giving 7.70 km/s at 360 km and 7.56 km/s at 600 km. The geometry is shown in Fig. 1. The satellite carries a regenerative eNodeB (or gNB) and serves a set of spot beams; the UE is a standard handset located inside a beam and possibly travelling with velocity $\mathbf{v}_u$.

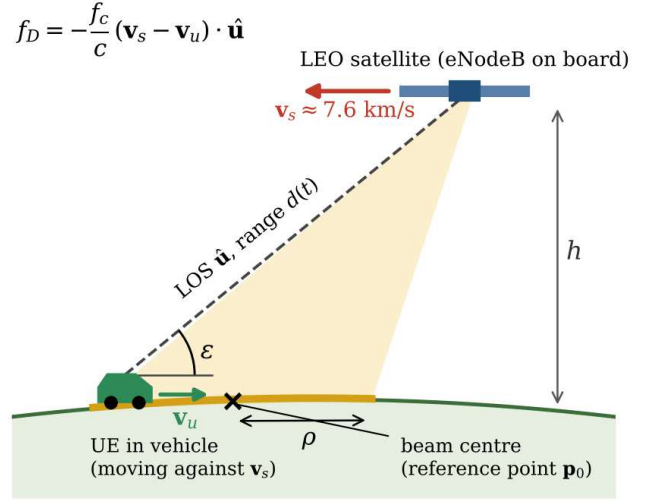


Fig. 1. Geometry of the D2C service link. The satellite moves with velocity $\mathbf{v}_s$; the UE inside a vehicle moves with velocity $\mathbf{v}_u$. The Doppler shift depends only on the projection of the relative velocity onto the line of sight (LOS). The network compensates Doppler for the beam-centre reference point $\mathbf{p}_0$; users at distance up to ρ from it see a residual offset.

B. Doppler Shift with UE Mobility

Let $\hat{\mathbf{u}}$ be the unit vector from the UE to the satellite and $d(t)$ the slant range. The range rate is $dd/dt = (\mathbf{v}_s - \mathbf{v}_u) \cdot \hat{\mathbf{u}}$, and the received frequency offset at carrier f_c is

$$f_D = -\frac{f_c}{c} (\mathbf{v}_s - \mathbf{v}_u) \cdot \hat{\mathbf{u}} \quad (2)$$

where c is the speed of light and $f_D > 0$ when the satellite approaches. Because the scalar product is linear, (2) separates into a satellite term and a vehicle term,

$$f_D = f_D^{\text{sat}} + f_D^{\text{veh}}, \quad f_D^{\text{veh}} = \frac{f_c}{c} v_u \cos \varepsilon \cos \Delta \alpha \quad (3)$$

where ε is the elevation angle and $\Delta \alpha$ is the angle between the vehicle heading and the horizontal direction to the satellite. Equation (3) makes an important point explicit: what matters is not the magnitude of the vector sum $\mathbf{v}_s - \mathbf{v}_u$ but its projection onto the LOS. A ground vehicle can contribute at most $v_u \cos \varepsilon$, which vanishes at zenith and is largest at low elevation.

C. Closed-Form Satellite Doppler

For a pass through the zenith of the UE (the worst case for Doppler rate) and ignoring Earth rotation, let $\psi(t) = \omega_s t$ be the Earth-central angle between the UE and the sub-satellite point and $r = R_E + h$. The slant range and satellite Doppler are

$$d(\psi) = \sqrt{R_E^2 + r^2 - 2R_E r \cos \psi} \quad (4)$$

$$f_D^{\text{sat}}(t) = -\frac{f_c v_s \sin \psi(t)}{c d(\psi)} \quad (5)$$

Using the law of sines in the Earth-centre/UE/satellite triangle, $\cos \varepsilon = r \sin \psi / d$, so the magnitude can be written directly in terms of elevation:

$$|f_D^{\text{sat}}| = \frac{f_c v_s R_E}{c r} \cos \varepsilon \quad (6)$$

Differentiating (5) and evaluating at $\psi = 0$ gives the maximum Doppler-rate magnitude, which occurs at zenith where the Doppler itself is zero:

$$|df_D/dt|_{\max} = \frac{f_c v_s^2 R_E}{c r h} \quad (7)$$

Equation (7) scales approximately as $1/h$, so lowering the orbit from 600 km to 360 km increases the peak Doppler rate by about 79%.

D. Earth Rotation

Earth rotation adds a ground velocity of $\omega_E R_E \cos \varphi$ at latitude φ , i.e. at most 465 m/s at the equator (422 m/s at 24.7°N). This term is deterministic, known from the ephemeris, and common to all users of a beam, so it is removed by the same compensation as the satellite term and has a negligible effect on the *differential* quantities analysed below. It is therefore omitted from the residual analysis, as in [8].

E. Beam-Centre Compensation and Round-Trip Residual

Let $v(\mathbf{p}) = f_D(\mathbf{p})/f_c$ denote the relative Doppler at ground position $\mathbf{p}$ and $\mathbf{p}_0$ the beam centre. In the downlink the satellite transmits at $f_{DL}(1 - v_0)$, with $v_0 = v(\mathbf{p}_0)$, so a UE at $\mathbf{p}$ receives a residual offset

$$\Delta f_{DL}(\mathbf{p}) = f_{DL}[v(\mathbf{p}) - v(\mathbf{p}_0)] \quad (8)$$

A legacy LTE handset synchronizes its local oscillator (LO) to the received downlink and derives its uplink carrier from the same reference, within a tolerance δ_{LO} of ± 0.1 ppm [19]. Its uplink is thus transmitted with a relative error $v(\mathbf{p}) - v_0$, then experiences the uplink Doppler $v(\mathbf{p})$ on the way to the satellite, and is finally post-compensated by v_0 . To first order the residual uplink offset at the satellite receiver is

$$\Delta f_{UL}(\mathbf{p}) \approx 2f_{UL}[v(\mathbf{p}) - v(\mathbf{p}_0)] + \delta_{LO} \quad (9)$$

The factor of two is the *round-trip* effect: the uplink inherits the downlink residual through the LO and adds an equal Doppler of its own. Because $v(\mathbf{p})$ in (9) includes the vehicle term of (3), whereas v_0 refers to a fixed reference point, vehicle motion is never removed by beam-level compensation.

F. Residual-Doppler Gradient and Beam-Sizing Rule

For small beams the residual grows linearly with distance from $\mathbf{p}_0$. Differentiating (6) with respect to ground distance and using the flat-Earth relation $d\varepsilon/dx \approx \sin^2 \varepsilon/h$ gives the maximum gradient

$$G(\varepsilon) \approx \frac{f_{DL} v_s}{c h} \sin^3 \varepsilon \quad (10)$$

which is exact at zenith (141.9 Hz/km at 360 km and 1.99 GHz) and within about 20% of the exact spherical value down to 30° elevation. Combining (3), (9) and (10), the worst-case uplink offset in a beam of radius ρ is bounded by

$$|\Delta f_{UL}| \leq \frac{2f_{UL}}{f_{DL}} G\rho + \frac{2f_{UL} v_u \cos \varepsilon}{c} + |\delta_{LO}| \quad (11)$$

Requiring $|\Delta f_{UL}| \leq \Delta f_{th}$ for a threshold Δf_{th} and neglecting δ_{LO} yields the maximum beam radius

$$\rho_{\max} \approx \frac{\Delta f_{th} - 2f_{UL} v_u \cos \varepsilon / c}{2(f_{UL}/f_{DL})G(\varepsilon)} \quad (12)$$

Equation (12) exposes the trade-off at the heart of this paper. Near zenith, $G(\varepsilon)$ is large and $\cos \varepsilon$ is small, so the beam size is *geometry-limited*. At low elevation, $G(\varepsilon)$ falls as $\sin^3 \varepsilon$ while the vehicle term approaches its maximum, so the beam size is

vehicle-limited, and when $2f_{UL} v_u \cos \varepsilon / c \geq \Delta f_{th}$ no beam size is feasible.

G. Inter-Carrier Interference

A residual offset Δf normalized to the subcarrier spacing, $\eta = \Delta f/\Delta f_{sc}$, attenuates the useful subcarrier by $\text{sinc}^2(\eta)$ and leaks the remaining power into neighbouring subcarriers as ICI [21], [22]. For a large number of subcarriers the signal-to-ICI ratio is

$$SIR_{ICI} = \frac{\text{sinc}^2(\eta)}{1 - \text{sinc}^2(\eta)} \approx \frac{3}{(\pi\eta)^2} \quad (13)$$

In the downlink a single UE can estimate and remove its common offset, so (13) mainly governs the uplink, where the eNodeB receives SC-FDMA signals from several UEs with *different* residual offsets that cannot all be corrected at once.

IV. SIMULATION METHODOLOGY

All results are obtained from an exact three-dimensional vector model on a spherical Earth. Satellite position and velocity follow (1); ground points, beam centres and UE positions are generated on the sphere; Doppler is computed from (2) without small-angle approximations; and residuals are computed from (8) and (9). Worst-case values are found by exhaustive search over a dense grid inside each circular beam, and the maximum beam radius is found by bisection on the exact model, providing an independent check of (12). The Monte-Carlo study uses 2×10^5 users uniformly distributed over the beam area with uniformly random headings and a fixed random seed. The parameters are listed in Table I. The simulation code is available from the authors on request.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Orbit altitudes h	360, 520, 550, 600 km
Earth radius R_E	6371 km (spherical)
Downlink / uplink carrier	1.990 / 1.910 GHz (LTE Band 25)
Subcarrier spacing Δf_{sc}	15 kHz (LTE)
Minimum elevation	10° (raw Doppler), 30° (beams)
Beam radius ρ	0.5–50 km
UE speeds v_u	0, 120, 350, 500, 1000 km/h
UE frequency error δ_{LO}	± 0.1 ppm (excluded from figures)
Offset thresholds Δf_{th}	1.25 kHz and 2.5 kHz (PRACH)
Monte-Carlo samples	2×10^5 per scenario

V. RESULTS AND DISCUSSION

A. Raw Doppler Shift and Doppler Rate

Fig. 2 shows the satellite Doppler and its rate for a zenith pass at the four altitudes, and Table II summarizes the extreme values. The Doppler follows the characteristic S-curve, from about +47.6 kHz to −47.6 kHz at 360 km, crossing zero at zenith where the rate peaks at 1034 Hz/s. Lowering the orbit only slightly increases the maximum Doppler (+5% from 600 to 360 km) but sharply increases the rate (+79%) and shortens the pass: the satellite stays above 30° for only 151 s at 360 km versus 247 s at 600 km.

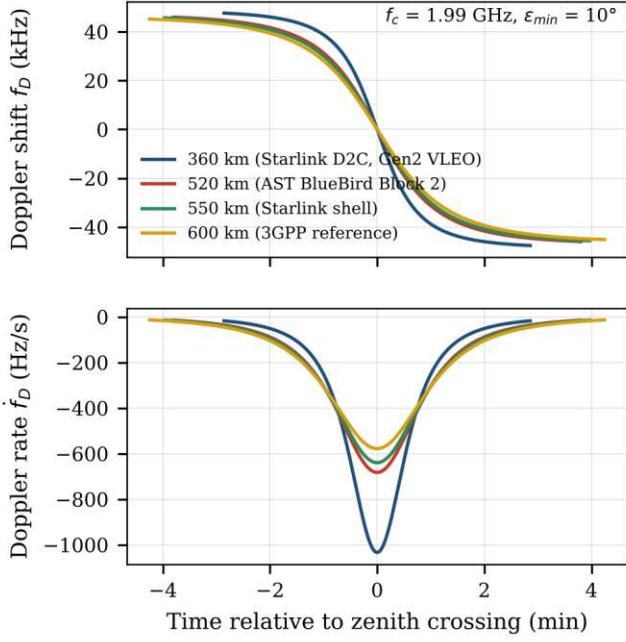


Fig. 2. Satellite Doppler shift (top) and Doppler rate (bottom) for a zenith pass at 1.99 GHz and minimum elevation 10° , for four representative D2C altitudes.

As a validation, the model gives 45.2 kHz (22.7 ppm) at 10° elevation and a peak rate of 578 Hz/s for 600 km at 1.99 GHz, compared with ± 48 kHz (24 ppm) and -544 Hz/s in TR 38.811 [8]. The small differences stem from the assumed satellite speed (7.5 km/s in [8]), the elevation range and Earth rotation, and are well within what is expected from these modelling choices.

TABLE II
SATELLITE DOPPLER CHARACTERISTICS AT 1.99 GHz

h (km)	v_s (km/s)	$ f_D $ at 10° (kHz)	$ f_D $ at 30° (kHz)	Max rate (Hz/s)	Pass > 30° (s)
360	7.70	47.6	41.9	1034	151
520	7.61	46.0	40.4	683	215
550	7.59	45.7	40.2	640	227
600	7.56	45.2	39.7	578	247

Zenith pass, non-rotating Earth. Rate magnitude given; its sign is negative.

B. Effect of a Counter-Moving Vehicle

Fig. 3(a) plots the total Doppler magnitude versus elevation at 360 km when the UE moves directly towards the satellite ($\Delta\alpha = 0$), the worst case suggested by the counter-moving intuition. The curves for all speeds are nearly indistinguishable: even an aircraft at 1000 km/h raises the relative speed by only 3.6% (from 7.70 to 7.97 km/s) and the LOS projection reduces this further at higher elevation. Fig. 3(b) isolates the vehicle term (3), and Table III lists its maxima.

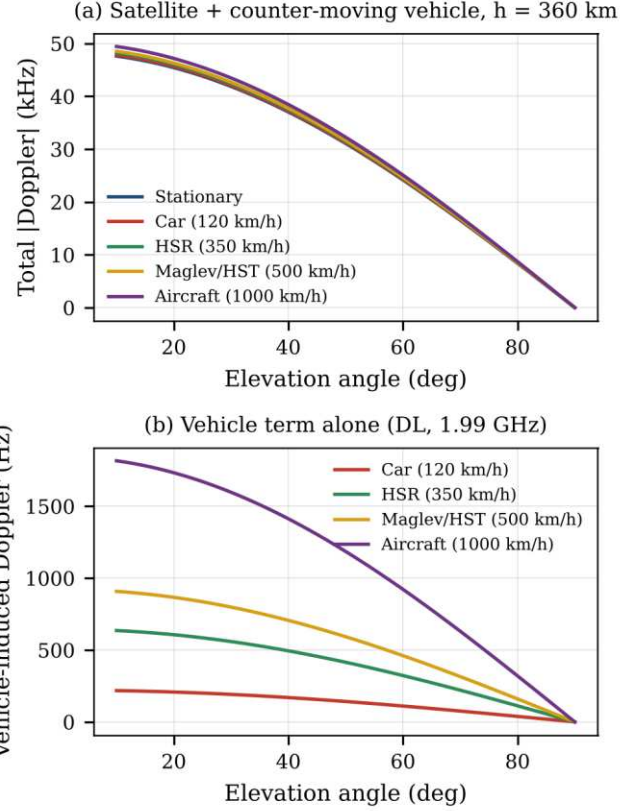


Fig. 3. (a) Total Doppler magnitude versus elevation at 360 km for a UE moving towards the satellite at different speeds. (b) Vehicle-induced Doppler term alone at 1.99 GHz.

TABLE III
MAXIMUM VEHICLE-INDUCED DOPPLER ($\cos \epsilon \cos \Delta\alpha = 1$)

UE platform	DL term (Hz)	UL round-trip (Hz)	% of sat. Doppler
Car, 120 km/h	221	425	0.5
HSR, 350 km/h	645	1239	1.3
Maglev/HST, 500 km/h	922	1770	1.9
Aircraft, 1000 km/h	1844	3539	3.8

Percentage relative to the 360 km satellite Doppler at 10° elevation.

Two conclusions follow. First, in absolute terms the vehicle never changes the order of magnitude of the Doppler; the counter-moving intuition overstates its effect because only the LOS component counts. Second, the vehicle term is of the order of hundreds of hertz to a few kilohertz, which is exactly the scale of the residual offsets that remain after compensation. Its importance must therefore be judged against the residual budget, not against the raw Doppler.

C. Residual Doppler after Beam-Centre Compensation

Fig. 4 maps the residual downlink Doppler (8) over a 25 km-radius beam at 360 km for beam-centre elevations of 90° and 45° . The iso-Doppler lines run cross-track, and the residual grows almost linearly along-track, reaching ± 3.54 kHz at the edge of the nadir beam but only ± 1.43 kHz at 45° , in agreement with the $\sin^3 \epsilon$ law of (10). The residual also varies slowly in time: at the edge of the nadir beam its rate is only 7.9 Hz/s, two orders of magnitude below the raw rate, so standard LTE frequency tracking handles it easily once acquired.

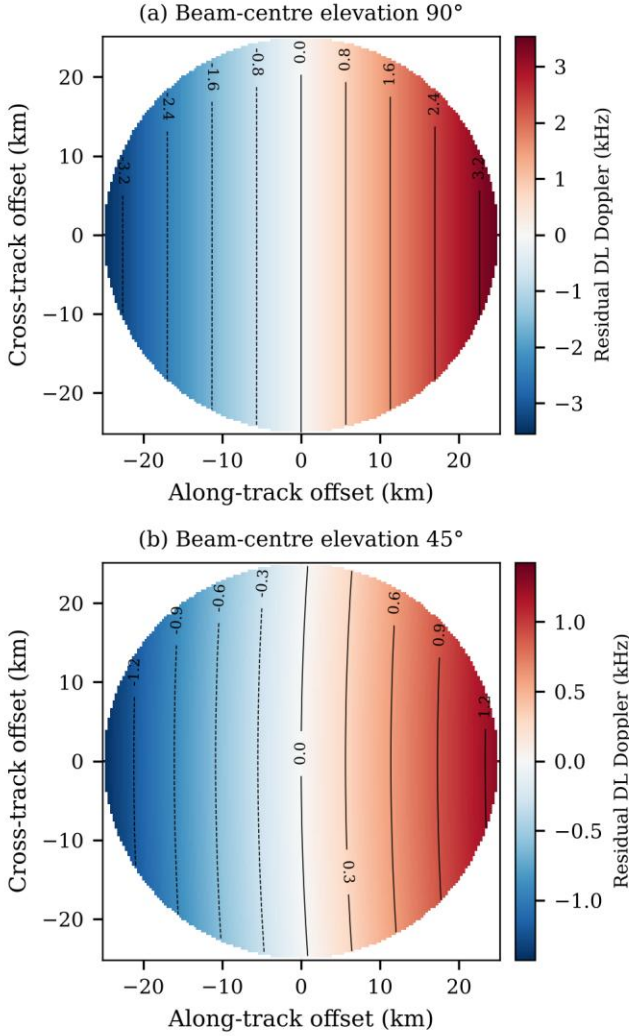


Fig. 4. Residual downlink Doppler after beam-centre compensation over a 25 km-radius beam at 360 km and 1.99 GHz: (a) beam centre at zenith; (b) beam centre at 45° elevation. Contours in kHz.

D. Uplink Offset Budget and Beam-Size Limits

Fig. 5 shows the worst-case uplink offset (9), including the round-trip factor and the vehicle term, versus beam radius. For a nadir beam [Fig. 5(a)] the curves for all speeds overlap because $\cos \varepsilon \approx 0$: the budget is geometry-limited, and the 1.25 kHz threshold is crossed at a radius of only about 4.6 km. For a beam at 30° [Fig. 5(b)] the geometric slope is much smaller, but the vehicle term adds a speed-dependent floor. For an aircraft this floor alone exceeds both thresholds, so no beam radius is feasible.

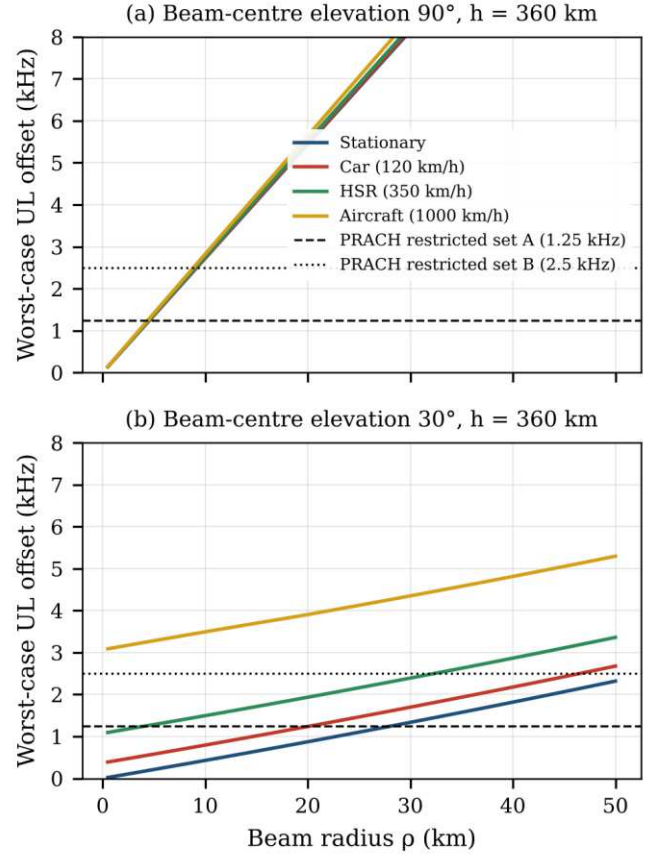


Fig. 5. Worst-case uplink residual offset (including round-trip doubling and vehicle motion) versus beam radius at 360 km: (a) nadir beam; (b) beam centre at 30° elevation. Dashed and dotted lines mark the PRACH restricted-set limits.

Table IV gives the maximum beam radius obtained by bisection on the exact model. The closed form (12) with the flat-Earth gradient (10) agrees with these values to within 5% for elevations of 60° and above. At 30° it is optimistic by 24–37%, because (10) underestimates the gradient at low elevation and large beams are no longer in the linear regime; using the exact beam-centre gradient reduces the error to 1–12%. Equation (12) is therefore a reliable first-cut design rule, to be refined numerically for low-elevation beams. Three regimes are apparent. Near zenith, vehicle speed is almost irrelevant, and the feasible radius is set by altitude (4.6 km at 360 km and 7.1 km at 550 km for 1.25 kHz). At 60° the vehicle already reduces the 1.25 kHz radius at 350 km/h by about half. At 30° the static radius is large (28–40 km), but a 350 km/h train shrinks it to 4–6 km and an aircraft makes the link infeasible.

TABLE IV
MAXIMUM BEAM RADIUS ρ_{MAX} (KM) MEETING THE UPLINK OFFSET
THRESHOLD

ε / v_u	360 km 1.25 kHz	360 km 2.5 kHz	550 km 1.25 kHz	550 km 2.5 kHz
90° / 0 km/h	4.6	9.2	7.1	14.2
90° / 120 km/h	4.6	9.1	7.1	14.2
90° / 350 km/h	4.5	9.1	7.0	14.0
90° / 1000 km/h	4.4	8.8	6.8	13.7
60° / 0 km/h	6.8	13.4	10.4	20.6
60° / 120 km/h	5.7	12.4	8.7	18.9
60° / 350 km/h	3.4	10.3	5.3	15.8
60° / 1000 km/h	—	3.9	—	6.0
30° / 0 km/h	28.2	53.5	40.2	76.5
30° / 120 km/h	20.3	46.5	29.0	66.5
30° / 350 km/h	4.2	32.3	6.0	46.2
30° / 1000 km/h	—	—	—	—

“—”: threshold exceeded by the vehicle term alone; no beam size is feasible. δ_{LO} excluded.

From (3) and (9), the vehicle term alone exceeds Δf_{th} when $\cos \varepsilon > c\Delta f_{\text{th}}/(2f_{\text{UL}}v_u)$. For an aircraft at 1000 km/h this occurs for all elevations below 69° with the 1.25 kHz threshold and below 45° with the 2.5 kHz threshold. A 350 km/h train never exceeds 1.25 kHz on its own (its maximum is 1239 Hz) but consumes almost the entire margin at low elevation.

E. Impact on Inter-Carrier Interference

Fig. 6 evaluates (13) for LTE’s 15 kHz spacing and marks the uplink offsets produced by the vehicle term alone. A car contributes $\eta = 0.03$ and a residual SIR of 25.8 dB, which is harmless. An HSR passenger reaches $\eta = 0.08$ and 16.4 dB, close to the 15 dB level reached at $\eta = 0.1$, which would cap the usable modulation order on the uplink. An airborne user reaches $\eta = 0.24$ and only 6.9 dB before any geometric residual is added. Because these offsets differ between UEs sharing a beam, they cannot be removed by a single receiver-side correction.

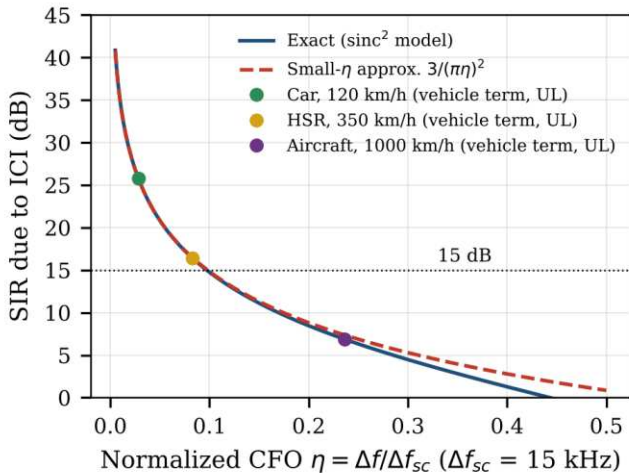


Fig. 6. Signal-to-ICI ratio versus normalized carrier frequency offset for 15 kHz subcarrier spacing. Markers show the uplink offset caused by vehicle motion alone at low elevation ($\cos \varepsilon \approx 1$).

F. Statistical Behaviour of the Uplink Offset

Worst-case bounds are pessimistic because they assume the most unfavourable position and heading simultaneously. Fig. 7

shows the complementary CDF of the uplink offset for users uniformly distributed over a 20 km beam at 360 km with the beam centre at 45° elevation. For static users the offset never exceeds 2.5 kHz, while 28% of users exceed 1.25 kHz purely because of geometry. HSR users raise these figures to 33% and 2.4%, with a 95th percentile of 2.29 kHz. In-flight users are strongly affected: 61% exceed 1.25 kHz, 26% exceed 2.5 kHz, and the median offset (1.62 kHz) is almost twice that of static users.

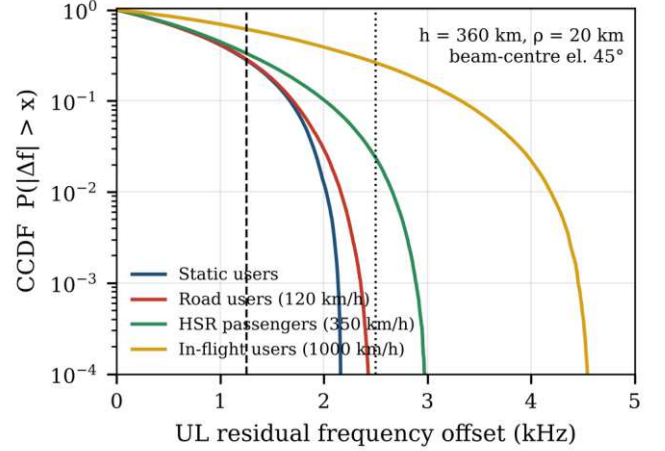


Fig. 7. Complementary CDF of the uplink residual offset for different user populations (2×10^5 users each, uniform position and heading), $h = 360$ km, $\rho = 20$ km, beam-centre elevation 45°.

G. Implications and Mitigation

The analysis suggests several design measures for D2C systems serving mobile users:

- **Elevation-dependent beam sizing.** Beam footprints should shrink towards nadir, where the gradient is largest, while low-elevation beams over HSR lines or air corridors should be sized by the vehicle term using (12).
- **Fine-grained compensation.** Earth-fixed cells with frequent update of the compensation reference reduce the geometric residual; large apertures that form narrow beams, as in recent D2C satellites [7], directly relax the constraint of Fig. 5.
- **High-speed PRACH configuration.** Cells covering transport corridors should use the extended restricted set, which doubles the tolerable offset to 2.5 kHz [18].
- **Doppler-aware uplink scheduling.** The eNodeB can estimate each UE’s offset from its reference signals, group UEs with similar offsets in adjacent resource blocks, and insert guard subcarriers between groups to limit multi-user ICI.
- **UE-side compensation.** Release-17 NTN handsets compute and pre-compensate their own service-link Doppler from GNSS and ephemeris [10]; as such handsets become widespread, the vehicle term can be removed at its source.
- **On-board relays.** For aircraft and trains, an on-board relay or small cell with a dedicated satellite terminal removes the high-speed user from the D2C link altogether.
- **Alternative waveforms.** In the longer term, delay-Doppler waveforms such as OTFS [23] are inherently robust to Doppler, but are not supported by legacy handsets.

Multipath also matters. A ground vehicle surrounded by local scatterers experiences a Doppler spread of up to $\pm f_D^{\text{veh}}$ around the LOS component [24], which reduces the channel coherence time and adds to the frequency offset considered here. In a strongly line-of-sight satellite channel this spread is weaker than the deterministic shift, but it adds further pressure on uplink channel estimation in fast vehicles.

H. Limitations

The study assumes ideal ephemeris and compensation, circular orbits, circular beams, a spherical non-rotating Earth for the differential analysis, and a line-of-sight channel without fading. The PRACH thresholds are used as conservative proxies; actual tolerance depends on the eNodeB receiver implementation. Field measurements with commercial D2C systems would be a valuable complement to this analysis.

VI. CONCLUSION

This paper has analyzed the Doppler effect on LEO Direct-to-Cell links serving unmodified handsets, including the case of users in fast vehicles moving opposite to the satellite. Raw Doppler at 360–600 km and 2 GHz reaches 45–48 kHz with rates up to about 1 kHz/s and is dominated entirely by the satellite. The intuitive concern that a counter-moving vehicle greatly increases the Doppler is not borne out in absolute terms, since only the LOS component of the vehicle velocity matters and it adds less than 4% even for an aircraft. After beam-centre compensation, however, the picture changes: the vehicle term cannot be compensated at beam level, it is doubled on the uplink by the round-trip effect, and it becomes comparable to or larger than the geometric residual. Closed-form expressions for the residual gradient and the maximum beam radius show that near-nadir beams are geometry-limited to a few kilometres, that low-elevation beams are vehicle-limited, and that airborne users cannot be served by legacy handsets at elevations below about 45° without additional compensation. These results provide quantitative guidance for beam design, PRACH configuration and scheduling in current and future D2C systems.

DATA AVAILABILITY

The simulation code and numerical results used in this study are available on reasonable request.

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