The effect of mobile internet on child marriage and teen pregnancy in sub-Saharan Africa *

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Abstract

Child marriage and teen pregnancy remain prevalent in sub-Saharan Africa. This paper examines the impact of mobile broadband internet (3G) expansion on these outcomes. We combine geo-referenced data on 3G coverage with individual-level marriage and fertility data from over 500,000 women-year observations across 20 sub-Saharan African countries between 2011 and 2022. Using two-way fixed effects, event studies, a stacked difference-in-differences, and an instrumental variables strategy, we find that adolescent girls exposed to 3G are between 1 and 6 percentage points less likely to marry and approximately 1 percentage point less likely to give birth, with no significant effects for older women. The effects are strongest among wealthier and more educated adolescents girls. Exploratory analyses suggest that increased access to information about family planning, shifting gender attitudes, and behavioral changes serve as mechanisms. Our findings imply that the expansion of 3G may be more effective than many conventional family planning interventions.

Keywords: teen pregnancy, child marriage, sub-Sahara Africa, 3G

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1 Introduction

Sub-Saharan Africa (SSA) has the highest rates of child marriage and teen pregnancy globally, with both phenomena linked to adverse health and economic outcomes (Chari et al., 2017; Field and Ambrus, 2008; Ganchimeg et al., 2014; Jensen and Thornton, 2003; WHO, 2024). According to the Child Marriage Data Portal (2024), one in five women worldwide were married before age 18, with prevalence highest in SSA. Similarly, UNICEF (2024) estimates that in 2022, 13% of women in SSA gave birth before turning 18. While child marriage has declined in Central and Southern Asia, progress in SSA has stalled over the past decade. Policy interventions aimed at reducing early marriage and fertility have shown limited effectiveness (Feyissa et al., 2023), and strategies that succeeded in Asia – such as large-scale family planning programs – have been less effective in Africa, where religious norms and lower acceptance of fertility control play a role (Caldwell and Caldwell, 2002). Emerging evidence suggests that access to media and information and communication technology (ICT) can influence fertility and marriage decisions (Billari et al., 2020; Bönisch and Hyll, 2023; Cassidy et al., 2024; Dewi et al., 2018; Ferrara et al., 2012; Guldi and Herbst, 2017; Kearney and Levine, 2015). This paper examines whether the rapid expansion of mobile broadband internet (3G) in SSA since 2011 – a key driver of social media access – has affected child marriage and teen pregnancy.

Our study draws on marriage information and records of birth histories from the Demographic and Health Surveys (DHS) and the geo-referenced Multiple Indicator Cluster Surveys (MICS). Our main dataset consists of 528,926 women-year observations gathered from 158,046 women and 20 DHS and 6 MICS surveys conducted between 2014 and 2022 covering 20 sub-Saharan countries. We combine the survey data with the geo-referenced mobile phone coverage data from the GSM Association (GSMA). We identify whether mobile broadband internet, specifically 3G or higher, is available in the woman's location of residence in the year of marriage and in the year before a child is born.[1] We then test if the expansion of 3G coverage influences child marriage and teen pregnancy using a two-way fixed effects model, a stacked diff-in-diff, an event study and an instrumental variables approach. In the TWFE and DiD models we include a variety of woman-level characteristics, time-varying locational controls, location-of-residence (cluster) dummies, country-year fixed effects, and woman-fixed effects. In the IV model, we control for geographical and infrastructural characteristics

[1] 3G mobile broadband, as opposed to 2G mobile broadband, introduced significantly higher-speed mobile internet, improved voice quality, and enhanced multimedia capabilities, such as use of social media.

of clusters, as the lightning instrument is only conditionally random.

Across all specifications, we find that 3G coverage significantly reduces child marriage and teen pregnancy, and effect sizes and significance levels are robust to choice of specification. Depending on the model, adolescent girls are between approximately 1 to 6 percentage points less likely to get married, and approximately 1 percentage point less likely to give birth when covered by 3G, while older women are unaffected. The economic magnitudes of these effects are substantial, as they imply an 8% reduction in child marriage and a 7% reduction in teen fertility, relative to control means of 24% and 20%, respectively. These effects are similar in magnitude to effect sizes of broadband internet and TV in Brazil, Europe and the United States; and are promising given the comparatively low success of family programs in SSA.

Heterogeneity analyses show that the effects on child marriage and teen pregnancy are particularly strong for wealthier and more educated women, suggesting that these women are likely the early adopters of the new technology. We perform complementary exploratory analyses to explore mechanisms, which suggest that knowledge about family planning, attitudes towards women and children and behavioral change, including the use of contraception, are likely to be drivers of the observed reductions in child marriage and teen pregnancy.

The identifying assumption underlying the TWFE model is that changes in 3G coverage in a given location and year are – conditional on control variables – as good as random. The main threat to the validity of the TWFE estimator is that it potentially suffers from bias under dynamic treatment effects (Borusyak et al., 2024; Callaway and Sant'Anna, 2021; Goodman-Bacon, 2021; Sun and Abraham, 2021). To address this potential bias we employ a stacked difference-in-difference (DiD) analysis (Goodman-Bacon, 2021; Wing et al., 2024), an event study (Sun and Abraham, 2021), and we use the imputation approach (Borusyak et al., 2024). TWFE, DiD and event study methods are valid estimators conditional on the lack of differential pre-trends. While we show that there exist no differential pre-trends for the fertility analyses, we can not confidently rule out differential pre-trends in the child marriage analyses. Therefore, we also implement an instrumental model using time-interacted lightning strikes as instrument (Flückiger and Ludwig, 2023; Manacorda and Tesei, 2020). For the teen pregnancy results, where we observe no pre-trends, all estimates fall within the confidence intervals of the TWFE estimates. For the child marriage results, where we can not confidently rule out pre-trends, the estimates from the DiD, event study, and imputation methods fall within the confidence intervals of the TWFE estimates, while the IV estimates differ slightly, but are still of similar magnitude.

We connect to a growing literature on the role of media in shaping gender norms, marriage, and fertility decisions. Media can modify important drivers of marriage and fertility through social learning and social influence or both (Balbo and Barban, 2014; Bernardi et al., 2007; Bongaarts and Watkins, 1996). Already in 1974, Inkeles and Smith (1985) showed that watching television and listening to radio installs different norms and values like limiting family size. Several television series, have shown to reduce (teen) fertility in both low- and high-fertility settings, such as Brazil and the US (Ferrara et al., 2012; Kearney and Levine, 2015). In a similar vein, the expansion of private television broadcasts had fertility-reducing effects in Germany and Indonesia (Bönisch and Hyll, 2023; Dewi et al., 2018). Moreover, exposure to cable television empowered women in India by increasing school enrollment, birth spacing, self-reported autonomy and by decreasing acceptability of domestic violence (Jensen and Oster, 2009). Exposure to edutainment via mobile cinema reduced child marriages in Pakistan (Cassidy et al., 2024). Likewise, the internet has been shown to have fertility-reducing effects for teenagers in the US, women's phone ownership has reduced fertility in Malawi, and mobile broadband internet reduced the prevalence of traditional social norms, including lower marriage and fertility rates in Jordan (Billari et al., 2020; Guldi and Herbst, 2017; Viollaz and Winkler, 2022).

More specifically, we contribute to a literature on the effects of mobile phones and 3G on development, which has so far been documented for political mobilization (Manacorda and Tesei, 2020), increases in women's political empowerment in Africa (Nkoa et al., 2023), reduction of corruption, improvement of confidence in the government (Guriev et al., 2021), increased labor force participation (Chiplunkar and Goldberg, 2022; Viollaz and Winkler, 2022), increased welfare among Indian fishermen (Jensen, 2007), and reduced poverty (Bahia et al., 2024). Mobile phones have also been documented to reduce fertility, lower gender inequality, increase contraceptive uptake, and lower maternal and child mortality, with the payoffs being largest in disadvantaged areas (Billari et al., 2020; Flückiger and Ludwig, 2023; Rotondi et al., 2020; Toffolutti et al., 2020).

This research also contributes to the role of multidimensional inequalities surrounding ICT, often referred to as the digital divide (DiMaggio et al., 2001; Norris, 2001) and how it relates to who benefits most from new technology. First, there is a gender divide (Alozie and Akpan-Obong, 2017; UNICEF, 2023). Young African girls have lower access to mobile phones than young boys, and when girls have a mobile phone in rural areas, they are sometimes even considered as 'prostitutes'

(Porter et al., 2020). African girls, compared to African boys, are less likely to use social media like Facebook (Fatehkia et al., 2018; Wildeman et al., 2023). Second, there is an urban-rural divide. Phone ownership is substantially higher in urban compared to rural areas, independent of both gender and age (Lembani et al., 2020; Porter et al., 2020). By studying heterogeneities in our sample we further contribute to quantifying the digital divide.

The remainder of the paper is structured as follows. Section 2 provides some background on child marriage, teen pregnancy, and 3G coverage in SSA, and describes potential relationships. Section 3 presents the data and construction of the estimation sample, and section 4 introduces our estimation strategy. The results including heterogeneity analyses and mechanisms are discussed in section 5 and section 6 concludes.

2 Background

2.1 Child marriage, teen pregnancy and 3G

Marriage is an important institution in the African culture as it signals the beginning of a woman's reproductive life. There are four traditional characteristics of marriage in SSA: (1) marriage was virtually universal for men and women in the 1950s and 1960s; (2) women are often considered marriageable when they reach puberty, resulting in early ages of marriage for women (3) typically there exist large age differences between husbands and wives; (4) polygyny is common (Garenne, 2022). In the 20th century, changes in marriage patterns occurred, particularly after independence, i.e., since 1960: age of first marriage for women started to increase and marriage rates for both men and women started to decrease (Shapiro and Gebreselassie, 2014). Improvements in women's education and income are considered to be the key drivers behind the rising age of marriage in 32 SSA countries (Garenne, 2004). However, until today, SSA has the highest rates of child marriage worldwide, and 9 out of 10 countries with the highest child marriage rates are situated in SSA (UNICEF, 2015). The negative consequences of early marriage for many development outcomes such as education, health of mothers and children, and intimate partner violence and labour market participation for women are well documented (e.g., Chari et al., 2017; Field and Ambrus, 2008; Hicks and Hicks, 2019; Jensen and Thornton, 2003).

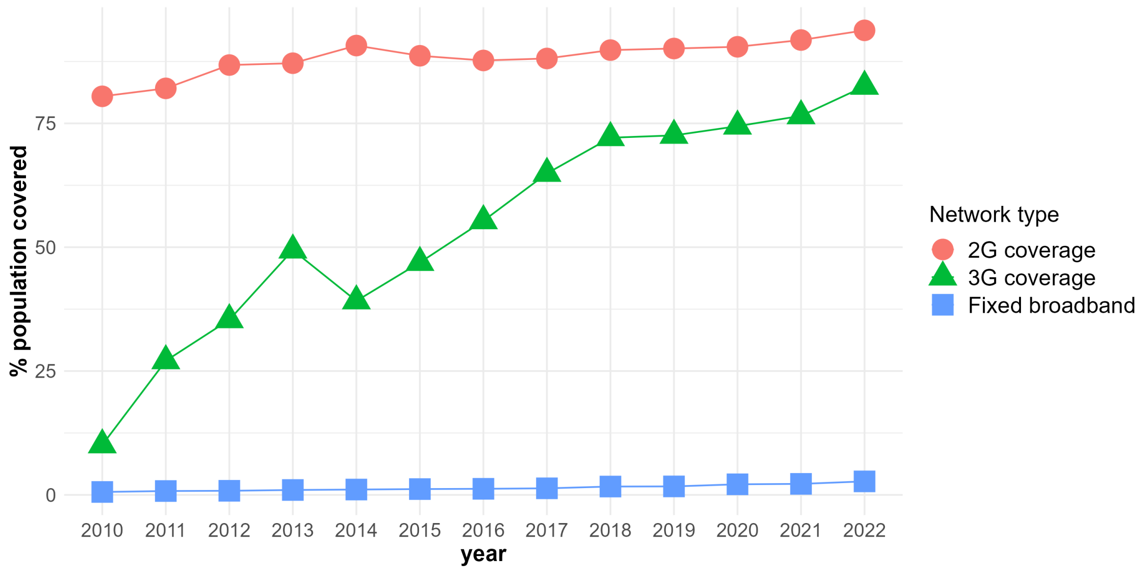
Giving birth to a child is another major event in a woman's life. Motherhood is considered a highly desirable role for women in most African societies (Ahonsi et al., 2019; Schaffnit et al., 2019).

Moreover, in SSA, women give birth to their first child early compared to other low- and middle-income countries (Kassa et al., 2018; UNICEF, 2015). As such, it might not be surprising that SSA has the highest teen pregnancy rates worldwide (Kassa et al., 2018; WHO, 2024; Yakubu and Salisu, 2018). In 2023, the adolescent birth rate for girls aged 10–14 years was 4.4 per 1000 women. For girls aged 15-19 the birth rate was 97.9 per 1000 women, compared to a global birth rate of 41.3 per 1000 women. Teen pregnancy has been linked to serious health issues for the mother and her child (e.g., low birth weight/premature birth, anemia, high blood pressure/pregnancy-induced hypertension, higher rate of infant mortality), school dropout, poverty, and domestic violence (Branson and Byker, 2018; UNICEF, 2015).

Teen pregnancy and child marriage are closely related and mutually reinforce each other, especially in SSA (Zgambo, 2022). Exemplary of this interrelation is existing evidence that delaying or preventing child marriage can help reduce teen pregnancy (UNFPA, 2012). In turn, teen pregnancy may be the gateway to child marriage (Agege et al., 2018), yet it can also be a consequence of child marriage (Menon et al., 2018). Once married, girls in SSA are expected to deliver a child without much delay, regardless of age (Ahonsi et al., 2019; Schaffnit et al., 2019).

Whereas the tradition of early marriage and fertility has been stable for many generations, 3G has developed very recently and rapidly. Figure 1 shows that 3G coverage in SSA grew from less than 10% in 2010 to more than 80% in 2022 (International Telecom Union, 2024). The 3G mobile network is a first-generation network that allows its users to freely browse the internet and use social media applications. The 3G signal affects internet usage on the extensive margin – by influencing the ability to go online – and on the intensive margin – by influencing the amount of time spent online – and qualitatively – by influencing what people do online (Guriev et al., 2021). In contrast to this sharp increase in 3G availability, fixed broadband internet access (ADSL or fiber-optic cables) hardly increased. As such, it is logical that the majority of Africans access the internet through their mobile phones (Bahia et al., 2024). They do so either on their own mobile phone or on the mobile phones of others, as African societies still incorporate strong sharing norms (Porter et al., 2015). This unique situation of 3G expansion in SSA sets the stage for our analysis.

Figure 1: Development of 2G, 3G and fixed broadband in sub-Saharan Africa



Notes: The figure shows the mean % of the population covered by 2G, 3G and the fixed broadband connections in sub-Sahara Africa. Source: ITU Digital Development: ICT Indicators Database (International Telecom Union, 2024)

2.2 Pathways from 3G to child marriage and teen pregnancy

We hypothesize that the expansion of the 3G network may influence child marriage and teen pregnancy through the provision of information, that may in turn change attitudes, preferences, beliefs and behaviour[2]. First, 3G coverage may reduce the cost of searching for information (Aker and Mbiti, 2010), thus improving the quality of adolescent girls' decisions. The 3G network allows its users to obtain information immediately, without having to wait for radio broadcasts or newspapers. Moreover, adolescent girls can take an active role in the search process by asking questions and looking for responses from multiple sources. For example, a teenager can go online, search, and identify where she can get contraceptives or where she can see a doctor. On the other hand, they may accidentally – by browsing the web – come across information on social media, in chat groups, or encounter advertisements that could change her behavior.

Information has proven of high relevance for fertility and marriage behavior. For example, Bau et al. (2024) show that providing information that modern contraceptives do not cause infertility at

[2]Appendix A.5 shows the conceptual model underlying how 3G coverage might influence child marriage and teen pregnancy through the information and changes in attitudes and preferences pathways. We set out from the cooperative bargaining model of the household and consider the availability of 3G as an alteration to the threat point.

an older age almost tripled contraceptive use compared to only giving a conditional cash transfer. Other examples of the value of information include (1) improved health knowledge due to mobile phone coverage which is likely to be an important explanation for reduced child mortality in SSA (Flückiger and Ludwig, 2023), and (2) decreased information search costs which are likely to explain how mobile phone ownership reduced fertility in Malawi (Billari et al., 2020).

Information may also change attitudes, beliefs and preferences toward what is acceptable and preferable behavior. One important feature of 3G is the ease of accessing social media, such as WhatsApp and Telegram. It may also allow users to engage online with other users in social networks (Rainie and Wellman, 2012). Online communities enable individuals to discuss ideas and information without physical proximity, resulting in contact with persons living in areas where other gender norms, fertility, and marriage patterns prevail. Moreover, the online environment allows individuals to challenge the cultural norms of their communities and to ask questions they would not dare to ask face-to-face without any fear of repercussions or real-life social costs, potentially allowing for a faster trickle-down of different ways of life (Rainie and Wellman, 2012).

Other studies have already reported the importance of changes in attitudes and preferences triggered by the availability of ICT and information. For example, soap operas have influenced women's fertility by changing family size preferences (Ferrara et al., 2012). Rotondi et al. (2020) and Arias (2019) show that improved access to information can change social norms towards gender equality and empower women to make more independent decisions. Abubakar and Dasuki (2018) show that WhatsApp, as one form of social media, enabled women within a community in Nigeria to push the barriers created by social norms dictating gender roles. Contact with other women in these WhatsApp group chats increased their autonomy and allowed them to voice their personal opinions.

3G coverage may also effect child marriage and fertility through spillovers from those with access to 3G to adolescent girls. Other studies found that having access to 2G increased women's labor market participation and income (Bahia et al., 2024). Access to mobile money, which is facilitated by mobile coverage, may also serve as protection against income shocks, and as such serve as protection against child marriage in certain contexts (Corno et al., 2020; Corno and Voena, 2016). Finally, 3G coverage can also increase screen time, increasing the opportunity cost of time and thus making dating or sexual intercourse less likely.

3 Data

Information on women's marriage and fertility behavior along with other women and household characteristics are taken from the Demographic and Health Surveys (DHS).[3] and the Multiple Indicator Cluster Surveys (MICS)[4] These surveys are nationally representative cross-sectional household surveys that collect data on women's marriage and full birth histories.[5] Our main dataset uses information from 20 DHS and 6 MICS surveys conducted between 2014 and 2022 and covers 20 sub-Saharan African countries, some of which are surveyed more than once (see Table A2 for a detailed list of all countries and surveys included).

As child marriage is typically defined as marriage before the age of 18, we select women between the ages 10 to 17 for our main models on child marriage. We construct the variable marriage as a dummy variable equal to 1 if a woman i in year t got married, and zero otherwise. In case a woman got married in a particular year, all subsequent year observations for that woman are coded as missing, as we assume that (child) marriage happens once, and a child married woman is unlikely to have divorced, and re-married again before she passes the age 18 threshold. For the additional analyses, to assess whether 3G also affects women's chances of getting married at older ages, we change the age selection of our sample in seven age groups [10-14; 15-19; 20-24; 25-29; 30-34; 35-39; 40-49]. The latter group spans 10 years to make sure we observe enough marriages as most women are typically married before the age of 40.

We define teen pregnancy as giving birth to a child before the age of 20. Therefore we use a dataset of women between ages 10 and 19 for our main models on teen pregnancy. We construct the variable "got child" as a dummy variable equal to 1 if a woman i in year t gave birth, and zero otherwise. Unlike the marriage data, a woman stays in the data after she gave birth to a child as she can give birth to a subsequent child even during her teens. We also test whether 3G affects women's probability of giving birth at older ages using the same age groups as described above for the child marriage analysis.

To measure 3G coverage, we use mobile coverage explorer data, which provides yearly rep-

[3] www.dhsprogram.com

[4] mics.unicef.org

[5] The sampling strategies of these surveys – to create a nationally representative, randomly selected sample of households – are to first randomly select a subset of non-overlapping geographical areas, called "clusters," which typically comprise communities, villages, towns, cities, or neighborhoods. In each of the selected clusters, all households are listed, and a random subset of 25-30 households are selected to participate in the surveys. Household members are first asked for basic household information, including a household roster before women aged 15 to 49 years are interviewed.

resentations of the area covered by mobile networks around the world. It has been created from submissions made directly to Collins Bartholomew[6] or the GSM Association (GSMA), which is an association that represents the interests of the mobile phone industry worldwide. This data is supplemented with coverage data created from OpenCellID, the world's largest open crowd information database of cell towers since 2019. We use digital maps of global 3G network coverage from 2011 to 2021 as 2011 marks the year when GSMA data on 3G for Africa became first available. As we are interested in the effect of having access to mobile broadband internet we consider not only 3G access but also include further improved access such as 4G. For each of the available country years, we identify the clusters with broadband internet coverage and refer to it as 3G coverage because 3G is by far the most prevalent form of available broadband internet.

We combine 3G coverage data with the DHS and MICS surveys based on the geocoded location of the residence of the woman. The main explanatory variable is a dummy variable that captures whether 3G coverage is available at the cluster location in a given year or not.

For our child marriage models, we have 490,946 women-year observations from 133,896 women. For our fertility models, we have 528,926 women-year observations gathered from 158,046 women. The former dataset is smaller because women that got married are coded as missing for subsequent years and the age restriction is more narrow. On average, a woman is observed for 3.3 years in the child marriage data, and for 3.7 years in the teen pregnancy data. Note that there is a seeming disconnect between the sample period of the household surveys and the 3G data as the earliest household survey data are from 2014. Yet, the final sample spans the period 2011 to 2021 since we make use of the DHS and MICS marriage and birth histories allowing us to backwardly expand into the years 2013, 2012, and 2011.

Table 1 shows the descriptive statistics for our main outcome and control variables. The first row shows that 19.6% of the teenagers in our sample gave birth to at least one child within the years they are included in our study. The yearly incidence rate of giving birth is 6.7%. The total incidence rate of child marriage in the sample is 23.9%, and the yearly incidence rate of marrying is 3.7%.

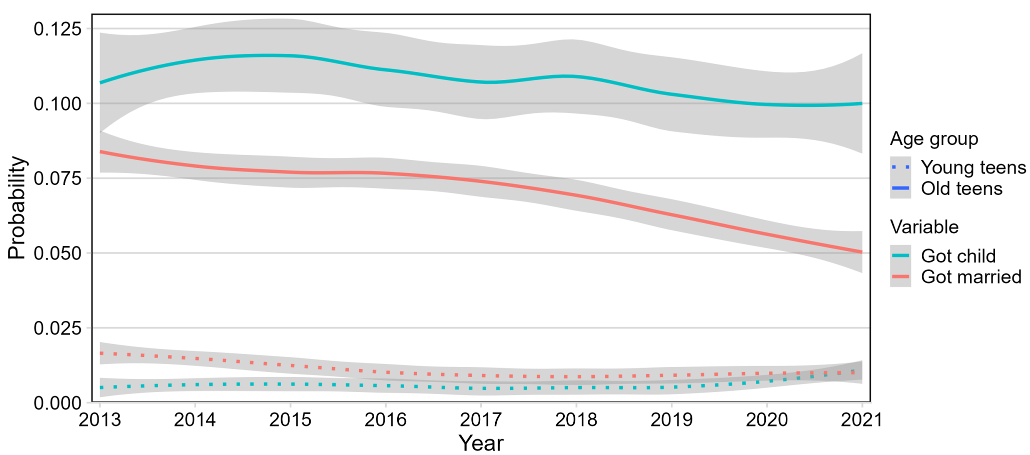
[6] https://www.collinsbartholomew.com/mobile-coverage-maps/

Table 1: Descriptive statistics of the main datasets

	Child marriage sample	Teen pregnancy sample
Mean prob. got married overall	0.239	
Mean prob. got married yearly	0.037	
Mean prob. got child overall		0.196
Mean prob. got child yearly		0.067
Mean 3G coverage	0.288	0.256
Minimum age	10	10
Maximum age	17	19
N women-year observations	490,946	528,926
N woman	133,896	158,046
Mean # obs. per woman	3.667	3.347

Over time we see a slight decrease in child marriage starting from 2017, especially for older adolescents aged 15 to 17 years (Figure 2). The decline in teen pregnancy for older adolescents (15 to 19 years) is less pronounced as also indicated by the wider confidence bands. For younger adolescents, aged 10 to 14 years, the marriage and pregnancy incidence rates are lower, yet remarkably stable over time.

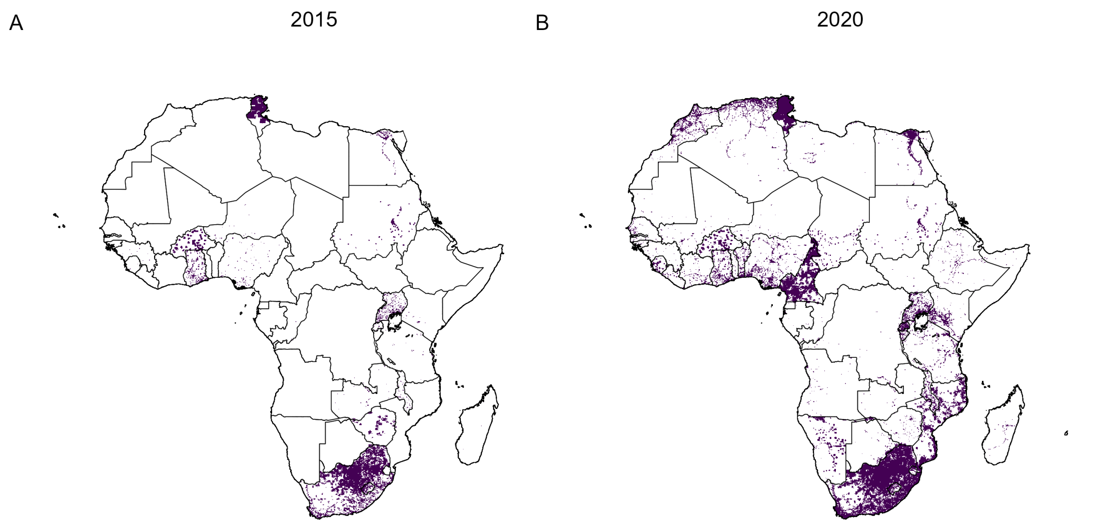
Figure 2: Trend in child marriage and teen pregnancy between 2013 and 2021



Notes: The figure shows the mean probability of giving birth and getting married for young teens (aged 10-14) in dotted lines and old teens (aged 15-19 for giving birth and aged 15-17 for getting married) in solid lines, for the sample of adolescent girls used in this paper. 2011 and 2012 are not included in this graph as only have data on two countries in those years. As such, it is not representative of the trend in the overall sample.

Average mobile internet coverage is low at around 25%. However, this average masks considerable spatial and temporal variation as shown in Figure 3 and Appendix Figure A1. The first available GSMA data on 3G coverage in Africa is from 2011, but only for a limited number of countries. Over the years, the number of countries with 3G data increased as well as the coverage rate within countries. We make use of the temporal and geographical variation in access to 3G to identify whether this variation influences child marriage and teen pregnancy.

Figure 3: Expansion of 3G coverage between 2015 and 2020



Notes: Panel A shows the availability of 3G coverage in Africa in 2015. Panel B shows this availability for 2020, as reported by GSMA.

4 Empirical framework

4.1 Two-Way Fixed Effects (TWFE)

The source of variation for the two-way fixed effects (TWFE) analysis comes from the staggered roll-out of the 3G network. This staggered roll-out generates geographic and temporal variation in 3G availability and, consequently, in child marriage and teen pregnancy. First, we estimate the effect of 3G coverage by comparing marriage and fertility outcomes of adolescent girls in places where 3G was and was not (control group) rolled out at two moments in time, namely before and after the arrival of the 3G signal. As such, the basis for our empirical analysis is the following linear regression model:

$$\text{Outcome}_{icjt} = \beta_0 + \beta_1 \text{3Gcov}_{cjt} + \beta_2 \mathbf{X}'_{iuct} + \beta_3 \mathbf{C}'_{uct} + \rho_c + \tau_{jt} + \zeta_i + \eta_{icjt}, \tag{1}$$

where Outcome_{icjt} is a dummy indicating whether an adolescent girl i living in cluster c in country j at time t got married, our first outcome of interest, or gave birth, our second outcome of interest. The main regressor 3Gcov_{cjt} is a dummy variable that takes the value 1 if the cluster where the adolescent girl lives has 3G coverage, as opposed to no 3G coverage at time t. For our fertility models, we use lagged variables (t-1) because, from the time of conception, it takes 9 months before a child is born and we are interested in the effect of 3G around conception and not birth.

$\mathbf{X}'_{iuct}$ is a matrix of individual control variables. In its most demanding version, this set of controls consists of fixed effects for age and the availability of 2G coverage. $\mathbf{C}'_{uct}$ is a vector of time-varying cluster controls at time t (and $t-1$ for our fertility models) as well as time-invariant cluster controls. These include the frequency of negative and positive rainfall shocks, mean yearly rainfall, night-time lights, minimum and maximum yearly temperature, interactions between a linear time trend and elevation, distance to the coast, distance to a main river, and distance to a nearby city. Appendix table A1 presents the data sources used to create these cluster controls, along with a short description of the content of these locational controls. Cluster fixed effects ρ_c absorb any time-invariant local characteristics, and the country $\times$ year fixed effects τ_{jt} account for country-specific annual shocks, like country-wide economic recessions. Additionally, we control for any time-invariant differences in woman characteristics by including woman-fixed effects ζ_i. Standard errors are clustered at the cluster level to account for the correlation of the error term across individuals within clusters.

The main threat to the validity of our empirical approach is that the TWFE estimator potentially suffers from bias under dynamic treatment effects, especially if treatment areas are not only compared to control areas, but also to areas treated earlier, or when there are heterogeneous treatment effects across groups due to differences in the timing of treatment (Borusyak et al., 2024; Callaway and Sant'Anna, 2021; Goodman-Bacon, 2021; Sun and Abraham, 2021). To provide additional support for the validity of our estimates, we employ four complementary approaches: (i) a stacked difference-in-difference (DID) analysis (Wing et al., 2024), (ii) an event study (Sun and Abraham, 2021), (iii) the imputation approach (Borusyak et al., 2024), and (iv) an instrumental variables (IV) model. In what follows we briefly detail the rationale for these models. Despite the acknowledged shortcomings of the TWFE estimator, we present the TWFE results as our main findings as they are perceived as easily comprehensible and intuitive. More importantly, for the data at hand, the complementary empirical approaches yield virtually identical results. We also challenge the robustness of our estimates to controlling for a wide range of locational controls, like rainfall shocks and night-time lights as proxies for local development. We also estimate a series of models in which we include region×time trends, city×time trends, select different sources of 3G coverage and leave some countries out of the sample (see Appendix A.2.5 for details).

4.2 Stacked DID and event study

First, we conduct a staggered, stacked (DID) analysis in which forbidden comparisons between regions that are both already treated but at different times are addressed (Wing et al., 2024). This method overcomes the limitations of the TWFE model by explicitly estimating separate treatment effects for each woman-year observation in our dataset, providing a more granular view of treatment impacts of 3G on child marriage and teen pregnancy, respectively. The regression is weighted by the cohort-specific synthetic unit weights applying Wing et al. (2024) weighting scheme. More details on the specification of this estimator are provided in Appendix A.2.1.

Second, we use the event study model by Sun and Abraham (2021) to account for potential dynamic treatment effects. The model is built on the DID framework but allows for multiple time periods and variation in the timing of treatment. In addition, this method avoids the bias introduced by assuming homogeneous treatment effects, thus providing more flexible and accurate estimates of the causal impact of the impact of 3G coverage. For more details, see Appendix A.2.2.

Third, to further refine our estimates, we add the imputation method proposed by Borusyak et al. (2024). This method provides an alternative for estimating the effect of the staggered 3G introduction, allowing for arbitrary heterogeneity in treatment effects and dynamics over time. The imputation method estimates a model on the not (yet) treated women and extrapolates this model to the women who gain 3G coverage. Appendix A.2.3 provides more details.

All three models come from the DID class and might not be fully able to address any remaining endogeneity. Therefore, we complement these models with an IV model.

4.3 Instrumental variable approach

To address concerns about differential pre-trends, specifically for the child marriage analysis, and remaining concerns about endogeneity, we also employ an IV model. The IV model exploits the fact that frequent lightning strikes – which have been shown to be conditionally random when controlling for a range of geographical and infrastructural characteristics of regions – delay the adoption of mobile phone technologies as established by in earlier studies Flückiger and Ludwig (2023); Guriev et al. (2021); Manacorda and Tesei (2020); Rotondi et al. (2020). Electrostatic discharges during storms damage mobile phone infrastructure and, in particular, antennas on the ground that transmit the signal in their vicinity, thus negatively affecting connectivity. The high costs of lightning conductors and other surge protection and weaker connectivity makes investment in 3G less profitable in areas with relatively more lightning strikes. Furthermore, poor connectivity makes the adoption of mobile phone technology less appealing. As a result, one would expect slower adoption of mobile phone technology in areas with high frequency of lightning strikes that fades out as more and more regions are covered. Therefore, we use local lightning frequency interacted with a time trend together with the squared term of this interaction as instruments for 3G coverage. More details about the IV approach can be found in Appendix A.2.4.

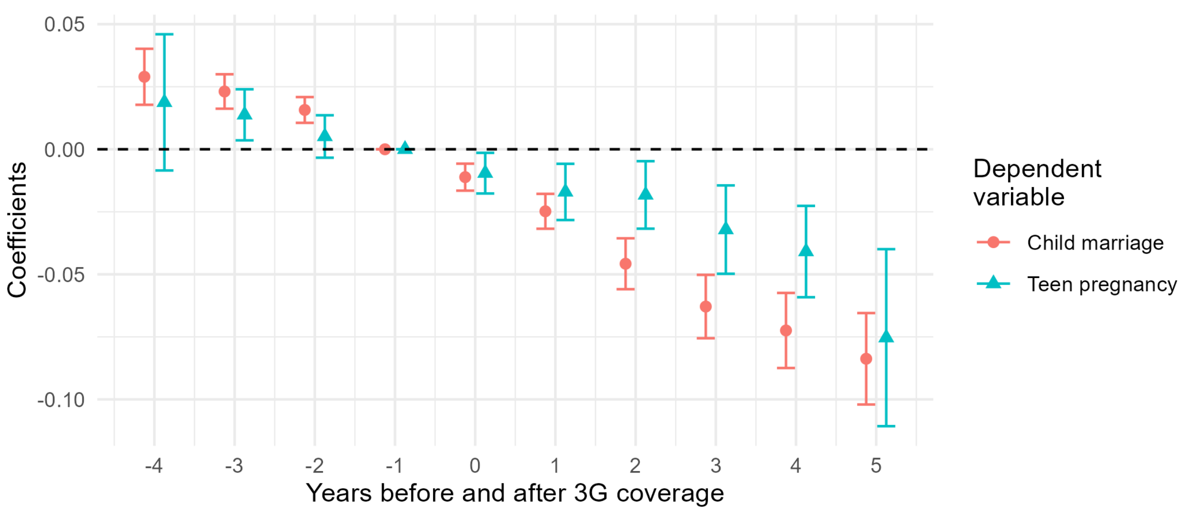
5 Results

5.1 3G coverage, child marriage and teen pregnancy

Before presenting the results of the effect of 3G coverage on child marriage and teen pregnancy, we show the results of an event-study framework based on Sun and Abraham's (2021) approach that allows us to check for the lack of differential pre-trends, which is a precondition for the identification assumption of the TWFE and DiD models.

Figure 4 plots the point estimates of the event-study regression estimates for 3G coverage on child marriage and teen pregnancy. While adolescent girls with 3G had a slightly higher chance to get married in the years prior to the arrival of 3G with coefficients around 0.025, and a small decline in the coefficients is visible, the confidence intervals from years -4 until -2 overlap with each other but not with -1. Therefore, we cannot rule out a pre-trend for the child marriage analysis. Yet, we observe a stark decline starting from period 0. In response to the introduction of 3G, we observe a decline in child marriage with some indication that it increases over time in absolute terms. Yet, confidence intervals for recent years are wide. Similarly, Figure 4 clearly shows the absence of a pre-trend for teen pregnancy. In the years prior to the roll-out of the 3G network, point estimates are statistically insignificant or close to zero with all confidence intervals overlapping. Starting with the first year of 3G availability ($t = 0$), the point estimates become significantly negative, meaning that the availability of a 3G signal reduces the likelihood of young girls giving birth. Importantly, there is no fading of the effect as the magnitude of the effects increases in absolute terms in later years, implying a cumulative process.

Figure 4: Event study estimates of the impact of 3G on child marriage and teen pregnancy



Notes: The figure depicts the event study point estimates and the 95% confidence intervals of the dynamic effects of 3G coverage on child marriage and teen pregnancy for the Sun and Abraham (2021) estimator. For the child marriage estimates, we included all women U18 (N = 315,000); for the teen pregnancy estimates, we included all women U20 (N = 353,677). Results are produced with the full set of controls, i.e., woman-fixed effects and locational controls.

Table 2 shows the effect of 3G coverage on child marriage. We consistently find a significant negative effect of 3G coverage on child marriage. Column 1 shows that – with our most parsimonious TWFE model that only includes cluster and country × year fixed effects, the probability of child marriage decreases by 1.0 percentage point when an adolescent girl's cluster is covered by 3G. As we add additional control variables in Column 2 and 3, the effect remains stable. In our most demanding specification in Column 4, we add time-varying woman and location characteristics and women fixed effects and show that an adolescent girl's chances to become a child bride are 1.7 percentage points lower when she gains access to 3G coverage compared to no access. This is a considerable decline in the incidence of child marriage as it corresponds to an 8.2% decrease in child marriage evaluated at the sample average child marriage rate of 20.5%. If we consider the weighted stacked DID result (Column 5), the average treatment effect (ATT) stemming from Sun & Abraham's approach (Column 6) and the Borusyak estimation (Column 7), we obtain larger reductions of 2.9, 3.4, and 2.6 percentage points, respectively. However, this is the main effect of having 3 or 4 years of 3G coverage. The coefficients for the first year are between 1.0 percentage points and 1.8 percentage points, and thus within the confidence intervals of the TWFE estimator (Appendix A.2.1). The Local Average Treatment Effect estimated with the lightning IV is 21 percentage points, which translates into an 6.1 percentage points reduction in ITT terms, given the share of compliers of 28.8%. While larger than the effects estimated in the other models, this effect is still within the same order of magnitude.

Table 2: Effect of 3G coverage on child marriage

	Child marriage							
	TWFE model 1	TWFE model 2	TWFE model 3	TWFE model 4	Weighted stacked DID	Sun & Abraham ATT	Borusyak et al. 2024	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
M3G coverage	-0.0098***	-0.0091***	-0.0235***	-0.0168***	-0.0290***	-0.0335***	-0.0257***	-0.2114***
	(0.0014)	(0.0015)	(0.0020)	(0.0022)	(0.0027)	(0.0037)	(0.0020)	(0.0396)
Cluster FE	yes	yes	yes	yes	yes[1]	yes	no	no
Country year FE	yes	yes	yes	yes	yes[1]	yes	yes	no
Year FE	no	no	no	no	no	no	no	yes
Woman controls	yes	yes	yes	yes	yes[1]	yes	yes	yes
Woman FE	no	no	yes	yes	yes[1]	yes	yes	yes
Locational controls	no	no	no	yes	yes[1]	yes	yes	yes
Obs.	490,946	435,924	435,924	352,352	352,187	918,036	277,474	315,000
R-squared	0.0977	0.1321	0.5299	0.5818	0.5468	0.6388		0.5862

Note: * $p < .1$; ** $p < .05$; *** $p < .01$; [1] fixed effects are cohort specific fixed effects. Standard errors (reported in parentheses) are clustered at the cluster level. Child marriage is 1 if a woman (under 18) got married in a given year and 0 otherwise. Woman controls include: 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city. Additional information can be found in appendix A.2.1 for the weighted stacked DID estimation, A.2.2 for the Sun & Abraham method, A.2.3 for the Borusyak et al. 2024 estimation, and A.2.4 for the IV specification and first stage results.

The results for teen pregnancy are similar to those for child marriage and are presented in Table 3. Using a parsimonious version of our estimating equation (1) in which we only control for country $\times$ year and cluster fixed effects, the resulting regression coefficient presented in Column 1 shows that teen pregnancy reduces by 0.9 percentage points when a teenager is covered by 3G. The coefficient increases when we control for woman characteristics and 2G coverage to 1.0 percentage point in Column 2. In Column 3, we restrict the comparison to women who gained access to 3G by including woman-fixed effects. As such, we compare the probability of giving birth of the same adolescent girl, in the years before and after getting 3G coverage. The resulting coefficient of 1.8 percentage points is significant at the 1 percent level, and larger than the coefficients without woman-fixed effects. This coefficient slightly decreases to a 1.3 percentage points reduction in teen pregnancy when we include location controls in Column 4. This implies a 7.1% reduction in the probability of giving birth, relative to the control mean of 18.0%. Again, Columns 5 to 8 show that the estimates of the ATT of the weighted stacked DiD, Sun & Abraham's and Borusyak's model reflect 3 or 4 years of 3G coverage, and fall within the confidence intervals of the TWFE estimator. The LATE of the IV estimator shows a reduction in 5.23 percentage points for those covered by 3G, which translates into an ITT of 1.3 percentage points, which again falls within the confidence intervals of the TWFE estimator.

The TWFE results on both child marriage and teen pregnancy are robust to the inclusion of region $\times$ year trends and the inclusion of urban $\times$ year trends (Table A8), the exclusion of the open crowd information data of 3G and 4G (Table A9), and the exclusion of any country in a Jackknife approach (Figure A2).

Table 3: Effect of 3G coverage on teen pregnancy

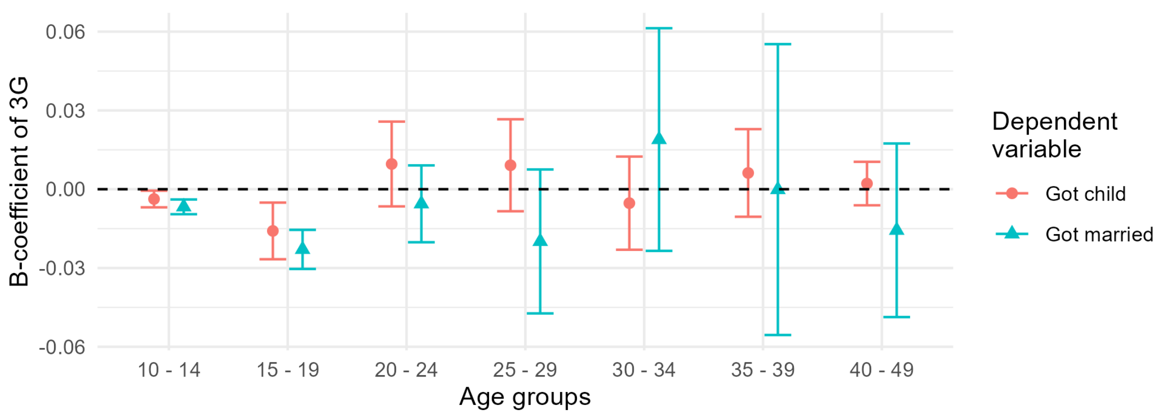
	Teen pregnancy							
	TWFE model 1	TWFE model 2	TWFE model 3	TWFE model 4	Weighted stacked DID	Sun & Abraham ATT	Borusyak et al. 2024	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
M3G coverage	-0.0087***	-0.0096***	-0.0182***	-0.0128***	-0.0195***	-0.0180***	-0.0188***	-0.0523*
	(0.0019)	(0.0019)	(0.0024)	(0.0031)	(0.0030)	(0.0049)	(0.0030)	(0.0295)
Cluster FE	yes	yes	yes	yes	yes[1]	yes	no	no
Country year FE	yes	yes	yes	yes	yes[1]	yes	yes	no
Year FE	no	no	no	no	no	no	no	yes
Woman controls	yes	yes	yes	yes	yes[1]	yes	yes	yes
Woman FE	no	no	yes	yes	yes[1]	yes	yes	yes
Locational controls	no	no	no	yes	yes[1]	yes	yes	yes
Obs.	528,926	501,166	501,166	387,384	386,486	770,916	302,300	353,677
R-squared	0.0758	0.1312	0.4135	0.4476	0.4445	0.5652		0.4496

Note: * $p < .1$; ** $p < .05$; *** $p < .01$; [1] fixed effects are cohort specific fixed effects. Standard errors (reported in parentheses) are clustered at the cluster level. Teen pregnancy is 1 if a woman (under 20) got a child in a given year and 0 otherwise. Woman controls include: 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city. Additional information can be found in appendix A.2.1 for the weighted stacked FE estimation, A.2.2 for the Sun & Abraham method, A.2.3 for the Borusyak et al. 2024 estimation, and A.2.4 for the IV specification and first stage results.

Next, we examine whether the negative effect of 3G on marriage and fertility is indeed specific to adolescent girls or whether there is an effect for older age groups as well. Figure 5 visualizes the regression coefficients from the TWFE for the effect of 3G coverage on the probability of getting married and giving birth for different age groups.

We find that the negative effect of 3G coverage on getting married and giving birth is strongest for women under the age of 20 and particularly for women aged 15-19. The effect of 3G coverage is also significantly negative for women aged 10-14 although the effect size is almost half of the effect size for women aged 15-19. We do not find an effect of 3G on the chances of getting married or giving birth for women aged 20 and older. This implies that it is certainly the youngest generation whose marriage and fertility patterns are affected by having access to 3G coverage, and that the younger generation is more susceptible to change their behavior following the introduction of 3G.

Figure 5: Effect of 3G coverage on marriage and fertility by age group



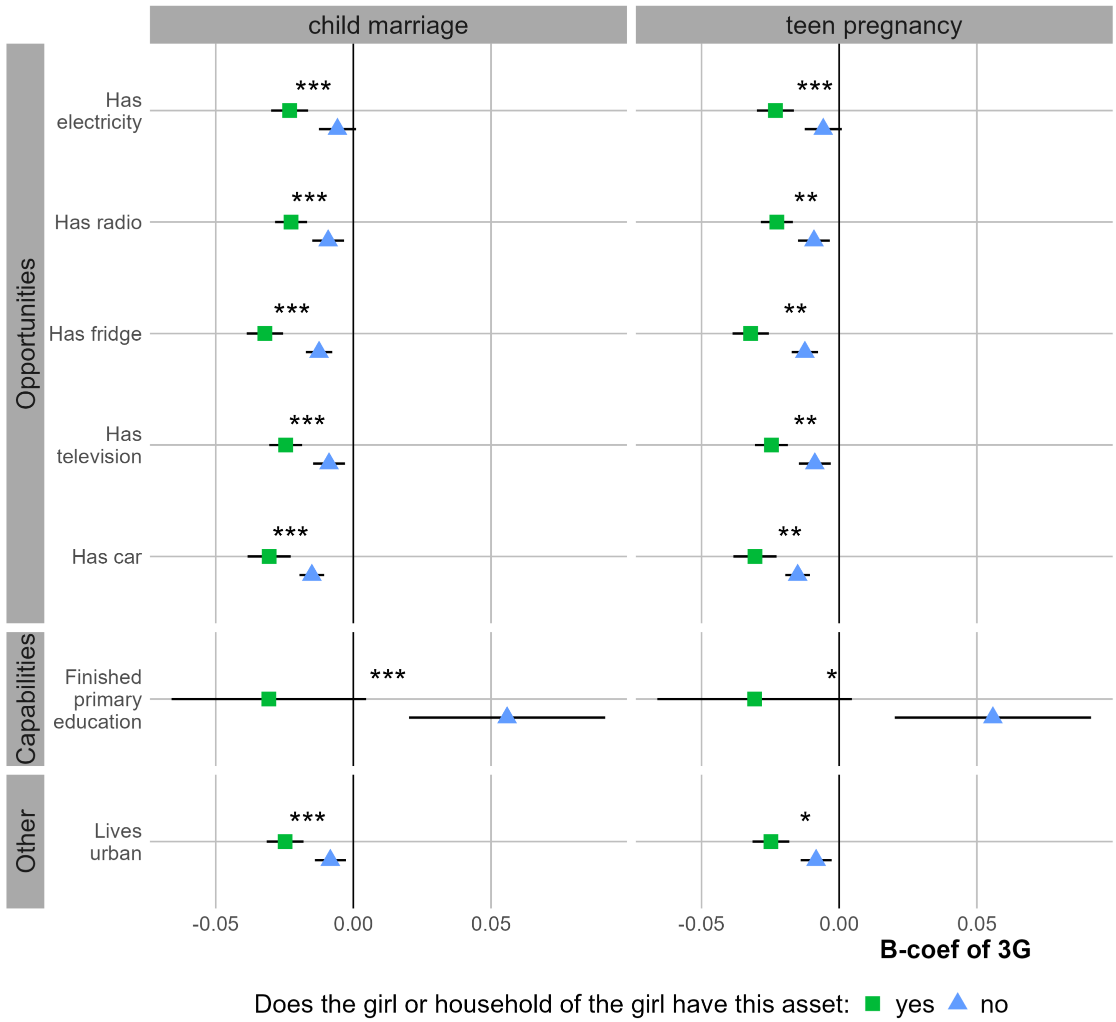
Notes: The Figure depicts the point estimates and 95% confidence intervals of the effect of 3G coverage on getting married and giving birth per age group using 14 different samples, 1 for each combination of age group and dependent variable. The results are derived with the TWFE model with the full set of controls, i.e., woman-fixed effects and locational controls that is also used for the estimates in Columns 4 in Table 2 and Table 3.

5.2 Heterogeneity analysis

Next, we test for heterogeneity in the effect of 3G coverage on child marriage and teen pregnancy by characteristics of the adolescent girl or her household. DiMaggio et al. (2001) and Norris (2001) identify several of these characteristics as important determinants of inequality in access to the internet. The results are presented in Figure 6. First, we test for heterogeneity by proxies for wealth of the household of the adolescent girl, namely by whether her household has access to electricity, owns a radio, a fridge, a television, or a car. We also show heterogeneity by the adolescent girls' primary education, and we test for differences in effects between urban and rural settings.

All our models show that the negative effect of 3G is stronger for adolescent girls in households with electricity, a radio, a fridge, a television, and a car. This is the case for child marriage as well as teen pregnancy. We also find that the negative effect of 3G is almost completely driven by adolescent girls who finished their primary education. This suggests that the ability to read and write matters for the effect of 3G coverage, possibly because it promotes basic digital literacy skills, which are key for accessing and distilling information from mobile internet (Geldof et al., 2021). The effect of 3G on adolescent girls who have not finished primary education is opposite for child marriage (and increase in child marriage), and not significantly different from zero for teen pregnancy. We further find that the negative effect of 3G is more prominent in urban areas, which are the areas where women are more likely to have the opportunities and capabilities for using 3G. These results reinforce the earlier identified digital divide with respect to 3G technology.

Figure 6: Effect of 3G coverage by adolescent girls' characteristics



Notes: * p < .1; ** p < .05; *** p < .01. The Figure depicts the regression estimates and the 95% confidence interval of the effect of 3G coverage for having (= green yes) and not having (= blue no) certain assets. The upper line stars show whether these differences are significant. Results are derived with the full set of controls, i.e., woman-fixed effects and locational controls. Child marriage is 1 if a woman under 18 got married in a given year and teen pregnancy is 1 if a woman under 20 gave birth in a given year and 0 otherwise. Table A10 shows the complete regression results for child marriage, Table A11 shows them for teen pregnancy.

5.3 Possible mechanisms

Our results so far document that the roll-out of 3G coverage reduces child marriage and teen pregnancy in SSA. We have, however, been silent about possible mechanisms underlying these reduced-form effects. The 3G signal itself cannot directly cause child marriage and teen pregnancy to decline. Thus, access to 3G must be a trigger for changes in knowledge, attitudes or behavior that ultimately lead to the observed results. To shed some light on the differences in knowledge, attitudes and behavior of young women who have access and who don't have access to a 3G signal, we estimate a series of regression models with alternative dependent variables coming from the DHS and MICS surveys to examine whether increased access to information and changes in attitudes and preferences may be the drivers of the effect on child marriage and teen pregnancy we identify. The data, along with the regression specifications are discussed in more detail in Appendix A.4. All subsequently presented results should be interpreted as suggestive, as the available data do not allow for the same rigor in the analysis as in the child marriage and teen pregnancy specifications since we only have data available for one moment in time, i.e., the moment of the survey.

We start by examining whether 3G had an effect on information. We assess whether 3G coverage is a predictor of adolescent girls' knowledge about modern contraceptives, awareness of family planning programs, and AIDS and sexually transmittable infections (STIs). Table 4 shows that, consistent with the idea that mobile broadband internet facilitates the exchange of information, we find evidence for differences in knowledge. Young women are better informed about modern contraceptives, family planning programs, and AIDS and STIs when they are covered by 3G.

Table 4: Effect of 3G on knowledge

	Knowledge channel		
	Knowledge of modern contraceptives	Heard about family planning	Heard of Aids or other STI
M3G coverage	0.0125***	0.0346***	0.0193***
	(0.0047)	(0.0113)	(0.0073)
Region FE	yes	yes	yes
Country year FE	yes	yes	yes
Woman controls	yes	yes	yes
Locational controls	yes	yes	yes
Obs.	42,712	39,085	38,357
R-squared	0.1346	0.2289	0.4033
Mean of dep. var.	0.9231	0.4719	0.778

Note: * p < .1; ** p < .05; *** p < .01. All women under 20 are included on which we have information on the dependent variable using only the most recent observation per woman. Standard errors (reported in parentheses) are clustered at the region level. Woman controls are the age of the respondent, whether the household has a car, television, fridge, electricity and whether the woman finished primary education. Locational controls include minimum and maximum temperature, rainfall, nightlights, elevation, ocean distance, river distance, travel times to the nearest city, and negative and positive rain shocks. More details on the estimation strategy and variables are provided in appendix A.4.

Next, we address whether adolescent girls change their attitudes and preferences concerning gender norms, preferred marriage behavior, and fertility in response to 3G coverage. In particular, we test whether 3G coverage predicts adolescent girls's acceptance towards wife beating and refusing sex, and their ideal family size. As shown in Table **??**, we find that 3G coverage makes women more likely to report that they find wife beating unacceptable, they are more likely to report that refusing sex is acceptable, and they report a lower ideal family size.

Table 5: Effect of 3G on attitudes and preferences

	Attitudes and preferences channel		
	Wife beating unacceptable	Refusing sex accepted	Ideal family size
M3G coverage	0.0752***	0.0445**	-0.2217***
	(0.0201)	(0.0190)	(0.0358)
Region FE	yes	yes	yes
Country year FE	yes	yes	yes
Woman controls	yes	yes	yes
Locational controls	yes	yes	yes
Obs.	64,668	7,990	37,667
R-squared	0.1352	0.2198	0.2845
Mean of dep. var.	3.2683	0.5894	4.2064

Note: * p < .1; ** p < .05; *** p < .01. All women under 20 are included on which we have information on the dependent variable using only the most recent observation per woman. Standard errors (reported in parentheses) are clustered at the region level. Woman controls are the age of the respondent, whether the household has a car, television, fridge, electricity and whether the woman finished primary education. Locational controls include minimum and maximum temperature, rainfall, nightlights, elevation, ocean distance, river distance, travel times to the nearest city, and negative and postive rain shocks. More details on the estimation strategy and variables are provided in appendix A.4.

Finally, we consider effects of 3G coverage on behavior. Column 1 in Table 6 shows that we do not find an effect of 3G coverage on the onset of contraceptive use (the age at which they use contraceptives for the first time). Column 2 shows, however, that 3G coverage has a significant positive effect on whether or not adolescent girls are currently using contraceptives. We also find that there is a decreased likelihood that women report to have started having sexual intercourse when they have 3G coverage (Column 3). Although this is only one facet of women's sexual and family formation, it is one effective way of avoiding teen pregnancy. It is also related to the finding that contraceptive use does not start earlier since girls who do not engage in sexual relationships are unlikely to use contraceptives. Thus, while young women are not starting the use of contraceptives at a younger age, they are more likely to keep using them when covered by 3G. This is an important finding as family planning programs often struggle with expanding contraceptive use.

Table 6: Effect of 3G on behavior

	Behavioral effects		
	Onset contraceptive usage	Current contraceptive usage	Sexual intercourse
M3G coverage	-0.0005	0.0088*	-0.0131***
	(0.0125)	(0.0050)	(0.0036)
Cluster FE	yes	no	yes
Region FE	no	yes	no
Country year FE	yes	yes	yes
Woman controls	yes	yes[1]	yes
Woman FE	yes	no	yes
Locational controls	yes	yes	yes
Obs.	56,128	42,712	449,161
R-squared	0.5476	0.1177	0.8849
Mean of dep. var.	0.0538	0.2588	0.4983

Note: * p < .1; ** p < .05; *** p < .01. All women under 20 are included on which we have information on the dependent variable. Onset contraceptive usage and sexual intercourse are panel datasets as used for our child marriage models only now with a different dependent variable, current contraceptive usage is a cross-sectional dataset including only the most recent observation of the woman. Standard errors (reported in parentheses) are clustered at the cluster level for onset contraception usage and sexual intercourse and at the regional level for current contraceptive usage. Onset contraceptive usage is 1 if a woman reports the start of using it and 0 otherwise. Current contraceptive usage is 1 if a woman is currently using. Sexual intercourse is 1 if a woman had for the first time sexual intercourse. Woman controls include: 2G coverage and fixed effects of age, and woman controls[1] are the age of the respondent, whether the household has a car, television, fridge, electricity and whether the woman finished primary education. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

6 Discussion and conclusion

We established a robust negative relationship between access to mobile broadband internet and child marriage and teen pregnancy in SSA. The effects of 3G are particularly pronounced for young women who have access to electricity, those who have higher wealth, live in urban areas and who have finished primary education.

The economic magnitudes of the effects of 3G on child marriage and teen pregnancy that we find are substantial: an 8% decrease in the likelihood of child marriage and a 7% decrease in the likelihood of teen pregnancy. Comparing our effect sizes with earlier studies that looked at the effect of ICTs and media, we see that our results align. Ferrara et al. (2012) reported a 7% decline in fertility due to the Brazilian telenovelas, Guldi and Herbst (2017) identified a 7% decline in teen fertility due to broadband internet in the United States, Kearney and Levine (2015) a 4% reduction in fertility due to MTV's TV show 16 and pregnant, and lastly, Bönisch and Hyll (2023) a 4-6% reduction in fertility due to the arrival of television.

We show that potential drivers of the effect of 3G coverage on child marriage and teen pregnancy are knowledge of contraceptives, STIs, and family planning; less favourable attitudes towards repressive behaviour against women, a lower desired fertility; and a decrease in the likelihood that women report that they have started sexual intercourse, and a higher likelihood of current contraceptive use. While we focus on the knowledge-attitude-behavior nexus because we have the most credible data to test this mechanism, we do not attempt to give a complete picture of all possible channels through which 3G might influence child marriage and teen pregnancy. Other studies found that having access to 2G increased women's labor market participation and income, which has the potential to protect women against harmful behaviors such as child marriage and teen pregnancy (Bahia et al., 2024); 3G is likely to have the same effect. It is known that having access to mobile money (through the 2G network) serves as protection against income shocks and as such, may serve as a protection mechanism for child marriage in certain contexts (Corno et al., 2020; Corno and Voena, 2023).

Our study is not without limitations. First, we rely on observational data. Yet, we can draw on a large sample with a considerable geographical and temporal spread. Moreover, the underlying surveys are representative of the population. Second, the staggered introduction of 3G poses the challenge of making forbidden comparisons. This is why we complement our TWFE with the weighted stacked DiD. For the child marriage analyses we can not exclude the presence of pre-trends, therefore we exploit conditional random variation in lighting as an instrument for 3G coverage, to estimate the effect on teen fertiltiy and child marriage. Also the IV model that uses the frequency of lightning strikes has challenges as lightning is time invariant and needs to be interacted with time. While the relevance of this instrument has been established by previous studies, we observe that the relationship between the lightning-trend and 3G coverage is not linear in out data. Therefore we use the lightning-trend and its squared term, to allow its effect to be more flexible. Third, our study of underlying mechanisms is only exploratory due to the lack of higher quality data. More research is needed on underlying drivers of the effects we observe.

We want to conclude with a word of caution. Our findings should not be interpreted in an overly optimistic spirit, inferring that access to mobile broadband internet will necessarily empower all young women in SSA. Our heterogeneity analysis shows that benefits from 3G coverage are heterogeneous. As access to mobile broadband internet grows, the disadvantage of not having a compatible device for different social and economic reasons may increase existing inequalities. Girls who do not have access to a phone might get one from a man/boy, but such gifts often include return favors rooted in traditions of patriarchy (Porter et al., 2020). On the other hand, externalities from girls with access to mobile broadband, through information, norms or (marriage) market dynamics could improve outcomes for girls without access to broadband. Moreover, girls searching for information on, for example, family planning, may encounter misinformation, suggesting that modern contraceptives cause infertility at older age, a claim widely disseminated in Africa (Boivin et al., 2020; Engelbert Bain et al., 2021). Similarly, social media does not automatically lead to improved decision-making, as individuals can self-select content based on their prior preferences and attitudes, leading to echo chambers.

The lesson learned from this paper is that acccess to mobile broadband internet has been serving as an empowerment tool for young women. We find an economically substantial effect, especially if we compare our results with targeted family planning programs that often struggle to reach substantial results (Feyissa et al., 2023). While program designers of family planning interventions who aim to empower adolescent girls are advised to address environmental factors, including financial barriers and community norms, 3G coverage seems to indirectly affect and alter these factors. As such, investing in 3G coverage, together with investments in socioeconomically structured opportunities and capabilities for girls who are at risk of falling behind, seems a promising policy strategy to reduce child marriage and teen pregnancy, and ultimately empower adolescent girls in SSA. Thus, programmes that target women empowerment and family planning would benefit from incorporating the use of mobile phones and internet in their programs.

In sum, this paper shows that the expansion of mobile broadband internet substantially reduced child marriage and teen pregnancy in SSA. The findings imply that a business-led endeavor, the expansion of mobile broadband coverage, can be a stepping stone for women's empowerment in developing countries. This calls for more creative approaches to development collaboration and for strategic partnerships between governments, donors, and businesses on the route to achieving SDG5 of gender equality by 2030.

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Appendix

A.1 Data

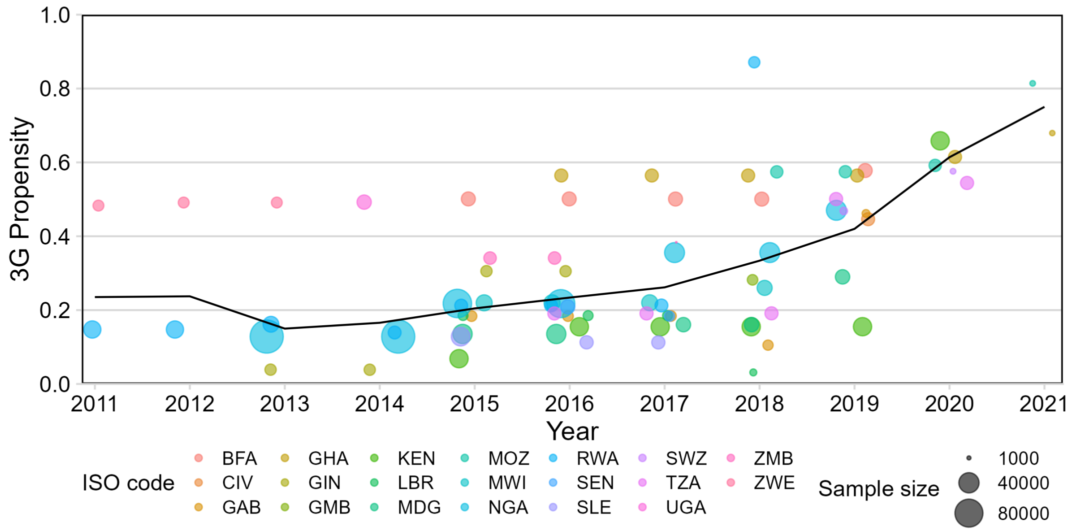
Table A1: Description of cluster covariates

Cluster covariates	Source	Short description
Temperature (°C)	CRU TS v. 4.05	The average minimum, mean, and maximum temperature at the cluster location. This dataset was produced by taking the average of the twelve monthly datasets for a given year.
Waterbody distance	GSHHG	The geodesic distance to either a lake, river, or coastline from the Global Self-consistent, Hierarchical, High-resolution Geography Database.
Elevation (m)	ETOPO1	The elevation at each cluster using the ETOPO Global Relief Model that integrates topography, bathymetry, and shoreline data from regional and global datasets to enable comprehensive, high-resolution renderings of geophysical characteristics of the earth's surface.
Urban center travel distance (minutes)	Malaria Atlas Project Accessibility to Cities	The average time (minutes) required to reach a high-density urban center, as defined by Pesaresi and Freire (2016) at the cluster location based on 2105 infrastructure.
Night light intensity	Version 1 VIIRS Day/Night Band Nighttime Lights	The average nighttime luminosity of the area at the cluster location for a given year.
Rainfall	CHIRPS	The yearly average rainfall (in mm) for each location. Rainfall shocks (negative and positive) are calculated based on the average calculated over the years 1981 - 2010. If the rainfall at a cluster location is 1.5 standard deviations lower or higher than the long-time average, it is defined as a shock (1.5SD lower is a negative shock, 1.5SD higher is a positive shock)
Lightning (flashes/km2/year)	NASA's Global Hydrology Resource Center, part of the LIS/OTD 0.5 Degree High Resolution Full Climatology (HRFC)	Observations from the 5-year OTD missions (1995-2000) and 8-year LIS missions (1998-2005) are included to express the bulk of lightning production. The lightning data consists of 0.05 degress grid cells at the equator.

Table A2: List of included surveys

Country	Source	Survey year
Burkina Faso	DHS	2021
Cote d'Ivoire	DHS	2021
Gabon	DHS	2019
Ghana	DHS	2022
Guinea	DHS	2018
Gambia	DHS	2019
Kenya	DHS	2022
Liberia	DHS	2019
Madagascar	MICS	2018
Madagascar	DHS	2021
Mozambique	DHS	2022
Malawi	MICS	2019
Nigeria	MICS	2017
Nigeria	DHS	2018
Nigeria	MICS	2021
Rwanda	DHS	2014
Rwanda	DHS	2019
Senegal	DHS	2018
Senegal	DHS	2019
Sierra Leone	MICS	2017
Sierra Leone	DHS	2019
eSwatini	MICS	2021
Tanzania	DHS	2022
Uganda	DHS	2016
Zambia	DHS	2018
Zimbabwe	DHS	2015

Figure A1: Development in 3G coverage of the used sample



Notes: The figure shows the mean coverage rate of 3G for young women aged 10 to 19 per country and year for the sample used in this paper.

A.2 Alternative estimators

A.2.1 Weighted stacked DiD analysis

An alternative to our baseline TWFE specification using a more stringent criterion for admissible control groups is a stacked difference-in-differences (DID) model. To ensure that appropriate comparisons are drawn, we manipulate our data so that "stacks" of cohorts are compared. A cohort is defined for every calendar year of the dependent variable. By aligning treatment (the arrival of 3G) by treatment-time (instead of calendar year), the approach is equivalent to a setting where the treatment takes place everywhere at once. This prevents negative weighting of some events that may occur within a staggered design. The regression is weighted by the cohort-specific synthetic unit weights applying Wing et al. (2024) weightings scheme.

As such, this approach ensures that within each cohort, the event study estimates are robust to both mis-specification and to bias which may be introduced by comparisons with already treated units as controls. We set $k_{pre} = 3$ and $k_{post} = 2$ to define a uniform event window for each cohort. We limit these data to the relevant calendar years so that each of the cohorts consist of 6 time observations. For each cohort, the treated group consists of all women who got access to 3G coverage in that year, and the corresponding control group includes all women who are either never treated or are not treated for at least k_{post} years after the focal adoption event. The baseline specification is as follows:

$$\text{Outcome}_{ict} = \beta_0 + \sum_{k=-3}^{2} \beta_k D_{kcit} + \beta_2 \mathbf{X}'_{cit} + \beta_3 \mathbf{Z}'_{cic} + \alpha_{ci} + \delta_{ct} + \rho_k + \zeta_{cjy} + \eta_{cit}, \tag{2}$$

where *Outcome* denotes whether woman i of cohort c gets married or gets a child at treatment time t. D_k are leads and lags of an indicator variable for 3G exposure. X is a vector of cohort-specific individual controls, such as 2G coverage and age-fixed effects, Z is a vector of cohort-specific cluster controls, α_{ci} are cohort-specific women fixed effects, which account for all time-invariant differences, δ_{ct} are cohort-event time fixed effects, ζ_{cjy} are cohort-country calendar year fixed effects, ρ_k are cluster fixed effects, η_{cjt} is the error term. The regression is weighted by the cohort-specific synthetic unit weights (Wing et al., 2024). Standard errors are clusters at the cluster level, which is the level at which the treatment occurs.

Table A3 shows the results of the weighted event study specifications that include women×cohort and event time×cohort fixed effects. The upper row shows that the aggregate ATT of 3G coverage durig 3 years after first getting covered by 3G is a 2.7 percentage point decrease in child marriage and a 2.0 percentage point decrease in teen pregnancy.

Table A3: Results of the weighted stacked DID analysis

	Weighted stacked DID Child Marriage	Weighted stacked DID Teen Pregnancy
Post treatment avg. effect	-0.029***	-0.0195***
	(0.0027)	(0.0030)
Event studies		
Treated x event-time -3	0.0323***	0.0055
	(0.0033)	(0.0037)
Treated x event-time -2	0.0210***	0.0055*
	(0.0025)	(0.0032)
Treated x event-time 0	-0.0100***	-0.0094***
	(0.0026)	(0.0030)
Treated x event-time 1	-0.0284***	-0.0234***
	(0.0029)	(0.0033)
Treated x event-time 2	-0.0488***	-0.0256***
	(0.0037)	(0.0039)
Cohort women FE	yes	yes
Cohort event-time FE	yes	yes
Cohort country-years FE	yes	yes
Cohort women controls	yes	yes
Cohort locational controls	yes	yes
Synthetic stacked weights	yes	yes
Obs.	352,187	386,486

Note: * p < .1; ** p < .05; *** p < .01. Standard errors (reported in parentheses) are clustered at the cluster level. Child marriage is 1 if a woman U18 got married. Teen pregnancy is 1 if a woman U20 gave birth. Cohort women controls include 2G coverage and fixed effects of age. Cohort locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

A.2.2 Sun and Abraham estimator

To further complement our baseline TWFE specification, we apply the Sun and Abraham (2021) estimator. This event study method is designed to provide more robust estimates of treatment effects in settings where the treatment is introduced across regions at different points in time. Importantly, the approach also accounts for heterogeneous pre-treatment trends. That means, with the event study method we account for the fact that some clusters might have been experiencing faster changes in child marriage rates or teen pregnancy rates even before 3G coverage was introduced. This adjustment helps to avoid bias that could arise from assuming that all units have parallel pre-treatment trends.

In our context, the treatment effect of 3G coverage on child marriage and teen pregnancy is identified by comparing the change in the probability of getting married or giving birth in clusters that received 3G coverage at different times to the changes in clusters that did not receive 3G coverage, or not within the immediate treatment window. As we observe an overall decline in both, child marriage and teen pregnancy (2), we cannot neglect it in our analysis. The Sun and Abraham method accounts for the pre-treatment trend and achieves comparability across regions by estimating the treatment effect using a weighted average of the different treatment cohorts, with each cohort being weighted according to the timing of their treatment. This prevents early-adopter clusters (those that received 3G coverage earlier) from disproportionately influencing the results.

Table A4: Sun and Abraham ATT estimators for child marriage

	Child marriage			
	Model 5 SA	Model 6 SA	Model 7 SA	Model 8 SA
M3G coverage	-0.0120***	-0.0105***	-0.0366***	-0.0335***
	(0.0020)	(0.0021)	(0.0027)	(0.0037)
Cluster FE	yes	yes	yes	yes
Country year FE	yes	yes	yes	yes
Woman controls	no	yes	yes	yes
Woman FE	no	no	yes	yes
Locational controls	no	no	no	yes
Obs.	490,943	407,733	407,733	315,000
R-squared	0.0980	0.1333	0.5327	0.5862

Note: * p < .1; ** p < .05; *** p < .01. Estimates represents the Sun Abraham estimators. Standard errors (reported in parentheses) are clustered at the cluster level. Child marriage is 1 if a woman (under 18) got married in a given year and 0 otherwise. Woman controls include 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

Table A5: Sun and Abraham ATT estimators for fertility

	Teen pregnancy			
	Model 1 SA	Model 2 SA	Model 3 SA	Model 4 SA
M3G coverage	-0.0081***	-0.0095***	-0.0207***	-0.0180***
	(0.0029)	(0.0029)	(0.0034)	(0.0049)
Cluster FE	yes	yes	yes	yes
Country year FE	yes	yes	yes	yes
Woman controls	no	yes	yes	yes
Woman FE	no	no	yes	yes
Locational controls	no	no	no	yes
Obs.	528,923	476,528	476,528	353,677
R-squared	0.0760	0.1318	0.4148	0.4496

Note: * p < .1; ** p < .05; *** p < .01. Estimates represents the Sun Abraham estimators. Standard errors (reported in parentheses) are clustered at the cluster level. Teen pregnancy is 1 if a woman (under 20) gave birth in a given year and 0 otherwise. Woman controls include 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

A.2.3 Borusyak et al. (2024) estimator

Another alternative to our baseline TWFE specification is the imputation method proposed by Borusyak et al. (2024). this approach is particularly useful for binary treatments with staggered rollouts, such as the introduction of 3G coverage, and allows for arbitrary heterogeneity and dynamic causal effects.

The estimation procedure for this method proceeds in three steps. In the first step, a model is estimated for all women who have not yet been covered by 3G, i.e. the never-treated and not-yet-treated women. The benchmark model in this case is the TWFE model as estimated in the main analysis. This step essentially establishes the counterfactual outcomes for women who have not been exposed to 3G coverage by modeling their outcomes using the pre-treatment periods and characteristics. In the second step, this model is extrapolated to those women that are covered by 3G (the treated women). Here, we impute the potential outcomes for the treated women under the counterfactual scenario where they had not received 3G coverage. In the third step, the mean estimated treatment effect is taken. This step provides a summary of the effect of 3G coverage on child marriage and teen pregnancy, adjusted for both pre-treatment characteristics and dynamic effects of the treatment over time.

Table A6: Results of the Borusyak estimator approach

	Borusyak et al. estimator	
	Child marriage	Teen pregnancy
3G ATT	-0.0257***	-0.0201***
	(0.0020)	(0.0026)
Time -4	0.0242	
	(0.0198)	
Time -3	0.0202	0.009*
	(0.0197)	(0.0050)
Time -2	0.0091	0.0026
	(0.0197)	(0.0049)
Time -1	-0.009	-0.0019
	(0.0198)	(0.0051)
Time 0	-0.0218***	-0.0186***
	(0.0021)	(0.0031)
Time 1	-0.0264***	-0.0243***
	(0.0026)	(0.0043)
Time 2	-0.0416***	-0.0186***
	(0.0059)	(0.0056)
Cluster FE	no	no
Country year FE	yes	yes
Woman controls	yes	yes
Woman FE	yes	yes
Locational controls	yes	yes
Obs.	277,474	302,300

Note: * $p < .1$; ** $p < .05$; *** $p < .01$. Standard errors (reported in parentheses) are clustered at the cluster level. Child marriage is 1 if a woman U18 got married in a given year and 0 otherwise. Teen pregnancy is 1 if a woman U20 gave birth in a given year. Woman controls include 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

A.2.4 IV analysis

Given that the TWFE, DiD and event study methods lead to invalid estimators in the case of differential pretrends, and we can not rule these out for the child marriage analyses, we instrument 3G coverage by the incidence of lightning strikes interacted with a trend and the squared term of this interaction. This approach is in line with previous studies that employed the incidence of lightning strikes, a time-invariant variable, interacted with a trend, in panel IV settings to study implications of mobile network expansion on confidence in government, political mobilization, sustainable development, and child mortality (Flückiger and Ludwig, 2023; Guriev et al., 2021; Manacorda and Tesei, 2020; Rotondi et al., 2020). These earlier studies either take a global approach or focus on the use of mobile phones, thus not exclusively considering the impact of 3G but rather 2G access.

While the studies above observe a linear relationship between the lightning trend and 3G coverage, we observe a U-shaped relationship[7]. To account for this non-linearity we introduce a quadratic interaction term as second instrument for 3G coverage, to allow for more flexibility. Put differently, the importance of the lightning time trend on predicting 3G decreases over time, which is captured by a positive estimate associated with the quadratic term. This reflects that the 3G market gets more and more saturated and as such, also the places with a comparably higher probability of lightning strikes will receive 3G eventually.

Formally, the IV model is set up as follows:

$$\text{3Gcoverage}_{ikt} = \beta_0 + \beta_1 \text{Lightning} * \text{t}_{kt} + \beta_2 (\text{Lightning} * \text{t}_{kt})^2 + \beta_3 \mathbf{X}'_{ikt} + \beta_4 \mathbf{C}'_{kt} + \rho_i + \tau_t + \eta_{ikt}, \quad (3)$$

$$\text{Outcome}_{ikt} = \beta_0 + \beta_1 \widetilde{\text{3Cov}}_{ikt} + \beta_2 \mathbf{X}'_{iuct} + \beta_3 \mathbf{C}'_{uct} + \rho_c + \zeta_i + \eta_{icjt}, \quad (4)$$

In our first-stage equation 3, the dependent variable $3Gcoverage_{ict}$ equals 1 when a woman i in cluster k has 3G coverage in year t. The included regressors are: time-interacted local lightning frequency ($Lightning * t$), the squared time-interacted local lightning frequency ($(Lightning * t)^2$), as well as the locational controls introduced in section (4 and collected in $\mathbf{C}'_{kt}$), woman controls ($\mathbf{X}'_{ikt}$), women fixed effects (ρ_i) and year fixed effects (τ_t). The error term is clustered at the cluster level. In the second-stage equation 4, we use the estimated 3G coverage of the first-stage (denoted

[7] The earlier literature has a global focus, often incorporates 2G, and typically covers a much longer time period than our panel covers, explaining these differences.

by $3\widetilde{\text{Cov}}_{ikt}$) to predict the two outcomes child marriage and teen pregnancy, respectively.

Table A7 shows the results. Lightning interacted with a time-trend negatively predicts 3G coverage as expected. The Effective F-Statics are 22.21 for the child marriage model and 31.75 for the teen pregnancy model. As such, these results confirm the validity of lightning strikes as instrument for 3G coverage. In the second stage, we find that that the predicted 3G coverage negatively predicts child marriage and teen pregnancy. The local average treatment effect (LATE) of 3G coverage on child marriage is a reduction of 21 percentage points, which translates into an ITT of 6 percentage points, based on a share of 28.8% of compliers. The LATE for 3G coverage on teen pregnancy is a reduction of 5 percentage points, which translates into a ITT of 1.3 percentage points, based on the share of compliers being 25.6%.

Table A7: Effect of 3G coverage on child marriage using IV method

	2SLS analysis	
	Child marriage	Teen pregnancy
First stage regression 2SLS		
	3G coverage	**3G coverage**
Lightning x time trend	-0.0024***	-0.0019***
	(0.0004)	(0.0005)
Lightning x time trend squared	0.0000***	0.0000***
	(0.0000)	(0.0000)
Effective F statistic	22.2102	31.7515
Woman FE	yes	yes
Year FE	yes	yes
Woman controls	yes	yes
Locational controls	yes	yes
Obs.	352,187	386,486
Second stage regression 2SLS		
	Child marriage	**Teen pregnancy**
3G coverage (predicted)	-0.2114***	-0.0523*
	(0.0396)	(0.0295)
Woman FE	yes	yes
Year FE	yes	yes
Woman controls	yes	yes
Locational controls	yes	yes
Obs.	352,187	386,486

Note: * p < .1; ** p < .05; *** p < .01.. Standard errors (reported in parentheses) are clustered at the cluster level. Child marriage is 1 if a woman U18 got married in a given year and 0 otherwise. Teen pregnancy is 1 if a woman U20 gave birth in a given year. Woman controls include: 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

A.2.5 Robustness analysis

Table A8: Inclusion of region×time trends and urban×time trends

	Child marriage		Teen pregnancy	
	Model 1	Model 2	Model 3	Model 4
M3G coverage	-0.0150***	-0.0110***	-0.0104***	-0.0084***
	(0.0024)	(0.0021)	(0.0033)	(0.0031)
Cluster FE	yes	yes	yes	yes
Country year FE	yes	yes	yes	yes
Woman controls	yes	yes	yes	yes
Woman FE	yes	yes	yes	yes
Locational controls	yes	yes	yes	yes
Region * time trends	yes	no	yes	no
Urban * time trends	no	yes	no	yes
Obs.	352,352	352,352	387,384	387,384
R-squared	0.5879	0.5837	0.4503	0.4480

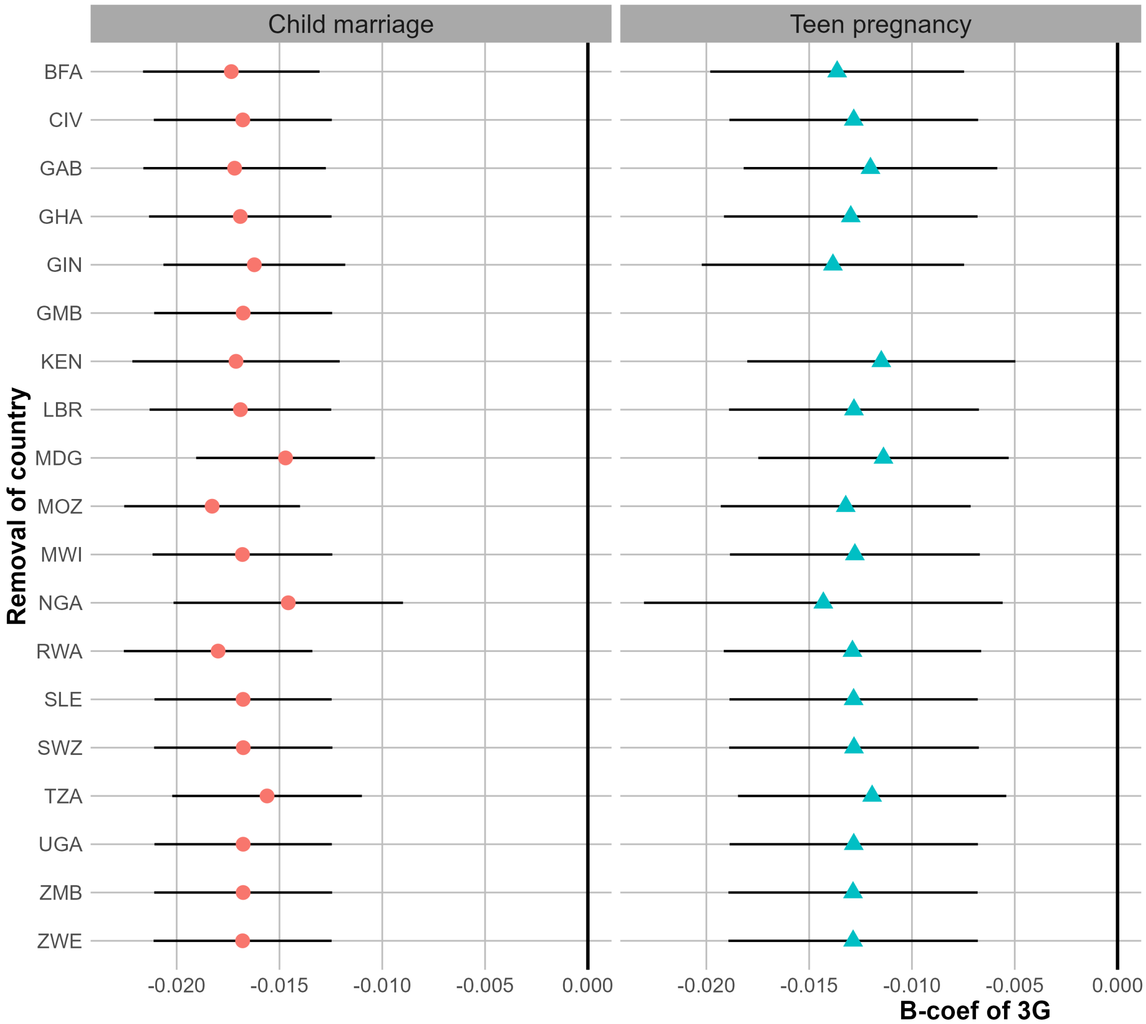
Note: * p < .1; ** p < .05; *** p < .01. Standard errors (reported in parentheses) are clustered at the cluster level. Child marriage is 1 if a woman (under 18) got married and 0 otherwise. Teen pregnancy is 1 if a woman (under 20) gave birth in a given year and 0 otherwise. Woman controls include 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

Table A9: Testing different sources of 3G coverage

	Child marriage		Teen pregnancy	
	Only 3G MCE	3G MCE + OCI	Only 3G MCE	3G MCE + OCI
M3G coverage	-0.0221***	-0.0169***	-0.0111***	-0.0118***
	(0.0030)	(0.0022)	(0.0036)	(0.0031)
Cluster FE	yes	yes	yes	yes
Country year FE	yes	yes	yes	yes
Woman controls	yes	yes	yes	yes
Woman FE	yes	yes	yes	yes
Locational controls	yes	yes	yes	yes
Obs.	344,968	348,768	381,917	384,630
R-squared	0.5789	0.5799	0.4407	0.4433

Note: * p < .1; ** p < .05; *** p < .01. Table tests the inclusion of different sources of 3G coverage and exlcudes 4G. MCE = mobile coverage explorere and OCI = open crowd information. Standard errors (reported in parentheses) are clustered at the cluster level. Child marriage is 1 if a woman (under 18) got married in a given year and 0 otherwise. Teen pregnancy is 1 if a woman (under 20) gave birth in a given year and 0 otherwise. Woman controls include 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

Figure A2: Testing influential countries



Notes: Figure depicts the regression estimates and a 95% confidence interval of the effect of 3G coverage on child marriage and teen pregnancy excluding one country. Results produced with full set of controls (i.e., woman fixed effects and locational controls). Child marriage is 1 if a woman under 18 got married in a given year and teen pregnancy is 1 if a woman under 20 gave birth in a given year and 0 otherwise.

A.3 Additional results

Table A10: Heterogeneous effects of 3G coverage on child marriage

	Child marriage							
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
M3G coverage	-0.0151***	0.0558***	-0.0058*	-0.0125***	-0.0092***	-0.0088***	-0.0084***	-0.0216***
	(0.0023)	(0.0182)	(0.0034)	(0.0025)	(0.0029)	(0.0030)	(0.0029)	(0.0023)
M3G × car	-0.0155***							
	(0.0040)							
M3G × primary school		-0.0865***						
		(0.0180)						
M3G × electricity			-0.0174***					
			(0.0034)					
M3G × fridge				-0.0197***				
				(0.0034)				
M3G × radio					-0.0135***			
					(0.0030)			
M3G × TV						-0.0157***		
						(0.0030)		
M3G × urban							-0.0164***	
							(0.0034)	
M3G × years 3G								-0.0106***
								(0.0015)
Cluster FE	yes	yes	yes	yes	yes	yes	yes	yes
Country year FE	yes	yes	yes	yes	yes	yes	yes	yes
Woman controls	yes	yes	yes	yes	yes	yes	yes	yes
Woman FE	yes	yes	yes	yes	yes	yes	yes	yes
Locational controls	yes	yes	yes	yes	yes	yes	yes	yes
Obs.	352,176	275,180	352,214	352,181	352,219	352,187	352,352	277,474
R-squared	0.5818	0.6114	0.5820	0.5820	0.5819	0.5820	0.5819	0.5853
Mean of dep. var.	0.0688	0.0745	0.0688	0.0688	0.0688	0.0688	0.0688	0.0739

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.005$. Standard errors (reported in parentheses) are clustered at the cluster level. Child marriage is 1 if a woman (under 18) got married in a given year and 0 otherwise. Woman controls include 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

Table A11: Heterogeneous effects of 3G coverage on teen pregnancy

	Teen pregnancy							
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
M3G coverage	-0.0113***	0.0121	0.0019	-0.0100***	-0.0067	-0.0057	-0.0077*	-0.0167***
	(0.0033)	(0.0154)	(0.0056)	(0.0036)	(0.0046)	(0.0046)	(0.0045)	(0.0032)
M3G × car	-0.0131**							
	(0.0061)							
M3G × primary school		-0.0295*						
		(0.0155)						
M3G × electricity			-0.0214***					
			(0.0059)					
M3G × fridge				-0.0118**				
				(0.0050)				
M3G × radio					-0.0106**			
					(0.0052)			
M3G × TV						-0.0132**		
						(0.0052)		
M3G × urban							-0.0090*	
							(0.0052)	
M3G × years 3G								-0.0069***
								(0.0020)
Cluster FE	yes	yes	yes	yes	yes	yes	yes	yes
Country year FE	yes	yes	yes	yes	yes	yes	yes	yes
Woman controls	yes	yes	yes	yes	yes	yes	yes	yes
Woman FE	yes	yes	yes	yes	yes	yes	yes	yes
Locational controls	yes	yes	yes	yes	yes	yes	yes	yes
Obs.	387,212	348,912	387,230	387,201	387,230	387,206	387,384	308,219
R-squared	0.4476	0.4458	0.4477	0.4477	0.4477	0.4477	0.4477	0.4401
Mean of dep. var.	0.1294	0.1327	0.1294	0.1294	0.1294	0.1294	0.1294	0.1352

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.005$. Standard errors (reported in parentheses) are clustered at the cluster level. Teen pregnancy is 1 if a woman (under 20) gave birth in a given year and 0 otherwise. Woman controls include 2G coverage and fixed effects of age. Locational controls include: frequency of negative and positive rainfall shocks, night-time lights, temperature, rainfall, and interactions between a linear time trend and elevation, distance to the coast, distance to a main river and distance to a city.

A.4 Method mechanisms

This appendix provides a more detailed description of the data, regression methodologies, and results as discussed in the subsection 5.3. In contrast to the main analysis presented in this paper (section 5), the data used to look at the information and attitudes mechanisms solely capture a snapshot of information at the time of the interview and are purely cross-sectional. Formally, the regression equation used to test the mechanisms is:

$$\text{Outcome}_{i,r,j,t} = \beta_1 3\text{Gcov}_{c,j,t} + \beta_2 \mathbf{X}'_{i,u,c} + \beta_3 \mathbf{Z}'_{u,c,t} + \rho_r + \tau_{j,t} + \eta_{i,r,j,t}, \tag{5}$$

where outcome$_{i,r,j,t}$ is the outcome for a woman i living in region r in country j at time t.

The main regressor $3\text{Gcov}_{c,j,t}$ is a dummy variable that takes the value 1 if the cluster where the woman lives has 3G coverage, as opposed to no 3G coverage at time t. $\mathbf{X}'_{i,u,c}$ is a vector of individual controls including age, 2G coverage, urban residence, finished primary education, having a car, radio, television, fridge, and electricity. $\mathbf{Z}'_{u,c,t}$ is a vector of cluster controls including negative and positive rainfall shocks, night-time lights, minimum and maximum temperature, and elevation, distance to the coast, distance to a main river, and distance to a nearby city. Cluster fixed effects are not included as the number of young women (aged under 20) is on average 6 per cluster. As such, we included region fixed effects ρ_c to absorb any time-invariant local characteristics. The country x year fixed effects τ_{jt} account for country-specific shocks, like country-wide economic recessions. Standard errors are clustered at the regional level to account for the correlation of the error term across individuals within regions.

The outcome variables for the knowledge channel are whether a woman had knowledge of modern contraceptives [1 = yes; 0 = no], heard about family planning through various channels [1 = yes, heard about it through at least 1 channel; 0 = no], and heard of Aids or other sexually transmittable infections [1 = yes, 0 =no]. The outcome variables used for the attitude channel are whether the young women believe that it is acceptable to beat a wife, to refuse sex, and women's ideal family size. Acceptance of wife beating is measured as a sum of the acceptability of wife beating on several occasions (beating justified if the wife goes out without telling the husband, if the wife neglects the children, if the wife argues with the husband, and if the wife burns the food). The minimum score is 0, wife beating is in none of the mentioned examples allowed, and the maximum score is 4, wife beating is in all occasions allowed. Whether a woman can refuse sex is a binary variable [1 = yes; 0 =no] and ideal family size is a numeric variable with a mean of 4.4. For the behavior channel, we included the onset of contraceptive usage [1 = start of use, 0 = no] using a panel-year model identical to the one of child marriage presented in this paper, current contraceptive usage [1 = yes; 0 = no] using a cross-sectional model as described in this section, and first time sexually active [1 = yes, had for the first time sexual intercourse; 0 = no] using again a panel-year model identical to the one of child marriage.

A.5 Conceptual framework: Cooperative bargaining model of the household

Conceptually, we root ourselves in the cooperative bargaining models of the household where bargaining power is a function of the outside options of the girl and her sexual partner/spouse, i.e., the welfare that both can obtain if they are not engaging in the relationship (Manser and Brown, 1980; McElroy and Horney, 1981). If the girl and her partner decide to engage in a relationship the advantages associated with being together outweigh those derived from abstaining from the relationship. The relationship generates a surplus, which will be distributed among its members, i.e., the girl and her (sexual) partner; the rule governing this distribution is the central issue and in our particular setup it is the change in the outside options that affects the bargaining power within the relationship, e.g., the girl's access to information through 3G and to many different lifestyles is likely to affect her preferences for early marriage and pregnancy.

In a typical, simple cooperative bargaining model, a household consists of only two members: a husband and a wife. The husband's utility function depends on his consumption of a bundle of private goods $U_h(c_h)$ and similarly the wife's utility function on her consumption of the private goods' bundle $U_w(c_w)$. If the two of them do not agree on a relationship, the payoff is represented by the threat point $(T_h(Z), T_w(Z))$, i.e., the utilities associated with a default outcome of staying single. This threat point depends upon a set of exogenous distribution factors Z.

The Nash bargaining model provides the leading solution concept in these bargaining models. The couple maximizes the Nash product:

$$N = [U_h(c_h) – T_h(Z)][U_w(c_w) – T_w(Z)], \quad (6)$$

subject to a pooled budget constraint. The Nash bargaining solution results in demand functions of the form:

$$c_i = f_i(p, y, Z), \quad (7)$$

where $i = h, w$, p reflects the prices of the private goods' bundles and y total family income. Thus, demands and individual utilities depend not only on prices and total family income but also on determinants of the threat point, i.e., the distribution factors Z. These distribution factors, in turn, can be altered by 3G. If they are altered such that the girl's threat point $T_w(Z)$ is increased, they would require a higher utility from engaging in a relationship. If the threat point is exorbitantly high, the girls might even decide not to engage in early marriage and childbearing as the utility derived from the relationship is lower than the outside option of staying single.