Abstract—This paper presents libtxsize, a library to estimate the size requirements of arbitrary Bitcoin transactions. To account for different use cases, the library provides estimates in bytes, virtual bytes, and weight units. In addition to all currently existing input, output, and witness types, the library also supports estimates for the anticipated Pay-to-Taproot transaction type, so that estimates can be used as input for models attempting to quantify the impact of Taproot on Bitcoin’s scalability.

libtxsize is based on analytic models, whose credibility is established through first-principle analysis of transaction types as well as exhaustive empirical validation. Consequently, the paper can also serve as reference for different Bitcoin data and transaction types, their semantics, and their size requirements (both from an analytic and empirical point of view).

I. INTRODUCTION

In most instances today, transaction-size estimates are used to construct favorable transactions that minimize transaction fees. These estimates rely on heuristics and simple tools [1]–[3]. The solutions available so far are, however, limited in scope: all are limited to giving estimates for transactions using only inputs of identical type; some are even limited to transactions that use the same input and output type. These shortcomings are addressed in this paper, which presents libtxsize, a library to give size, weight, and virtual size estimates for transactions with arbitrary inputs, outputs, and witnesses.

Although libtxsize can be used in the context of fee optimization, the library was developed to provide estimates that can serve as inputs for quantitative models whose projections provide objective data to assess the impact of future improvements on Bitcoin’s scalability. To this end, libtxsize includes support for the anticipated Pay-to-Taproot transaction type.

This paper is structured as follows. Digital signatures, which are used by Bitcoin to establish ownership of coins, are discussed and investigated as to their size requirements in Section II. The formats of Bitcoin transactions and their components, such as inputs, outputs, and witnesses, are presented in Section III and studied as to their size requirements. Section IV investigates the dynamic components of inputs, outputs, and witnesses, derives analytic estimates, and validates them using empirical data. Section V discusses how libtxsize integrates the findings of the previous sections in a bottom-up way. Finally, Section VI provides a summary and concludes the paper.

II. ENCODING OF PUBLIC KEYS AND SIGNATURES

Bitcoin uses public keys and signatures to establish ownership of funds. So far, Bitcoin relies on the elliptic curve digital signature algorithm (ECDSA) for signature verification. This, however, might change with BIP 340, which introduces Schnorr signatures. Both methods rely on elliptic curve cryptography (ECC), and use the same elliptic curve, secp256k1, defined in the Standards for Efficiency Cryptography (SEC) [4]. Despite these similarities, there are some differences between ECDSA and Schnorr signatures concerning the encoding of public keys and signatures in Bitcoin. These differences are discussed in the following.

A. Encoding of public keys

1) Encoding of ECDSA public keys: In ECC, public keys correspond to the $x$- and $y$-coordinates of points on an elliptic curve. The secp256k1 curve used by Bitcoin uses 32-byte numbers to represent these coordinates.

In case of ECDSA, these coordinates are encoded using a standard defined in the SEC [4]. Originally, Bitcoin only supported the uncompressed SEC format. This format includes a one-byte SEC prefix, which specifies the type of encoding (in this case, the uncompressed format), followed by the key’s two 32-byte $x$- and $y$-coordinates._encoding a public key in the uncompressed SEC format thus requires 65 bytes.

After some time, Bitcoin added support for the compressed SEC format, which reduces the size of the encoding significantly by taking advantage of the fact that a public key’s $y$-coordinate can be derived from its $x$-coordinate (with the exception of its sign). The compressed SEC format thus only includes a public key’s $x$-coordinate. The ambiguity concerning the $y$-coordinate’s sign is resolved using the SEC prefix: there are two magic numbers for the compressed SEC format; one indicates a positive $y$-coordinate, the other a negative one. By getting rid of 32-byte $y$-coordinate, the compressed SEC format allows public keys to be encoded using only 33 bytes.

Fig. 1 shows the share of uncompressed and compressed public keys in transactions over time. The empirical data reveals a steady decline in the use of uncompressed keys in

3For a given $x$-coordinate, the corresponding $y$-coordinates are obtained by solving the secp256k1 curve’s equation $y^2 = x^3 + 7$ for $y$. Note that $y^2$ implies two valid solutions, $y$ and $-y$, which differ only with respect to sign.
Fig. 1. (a) Public key encoding type and (b) histogram of signature sizes.

Bitcoin over the years, a development presumably driven by the reduction in fees for transactions using smaller public keys. In fact, in the recent past the share of transactions using uncompressed keys has been so low that, for practical purposes, they can be neglected. In light of this, for the following investigation, public keys are assumed to have a size of 33 bytes.

2) Encoding of public keys in Schnorr signatures: Public keys in Schnorr signatures also correspond to curve points. For Schnorr signatures, however, the encoding of public keys does not follow the SEC [4] standard. Instead, a custom encoding is used, which includes only a point’s x-coordinate. Ambiguity concerning the y-coordinate is resolved using the coordinate’s parity by defaulting to the even y value. The encoding of Schnorr public keys thus have a size of 32 bytes.

B. Encoding of signatures

1) Encoding of ECDSA signatures: ECDSA signatures for the secp256k1 curve consist of two 32-byte numbers, r and s, and Bitcoin’s encoding of such signatures follows the Distinguished Encoding Rules (DER) [5].

Per DER, each of the numbers, r and s, is prefixed by two bytes: one to encode the data type, which in case of Bitcoin is signed integer; the other to indicate the size of the following data—typically 32 bytes for the values r or s. So far, this makes for a total overhead of four bytes.

On top of that, there are two bytes at the beginning of each DER signature: one to indicate that the signature consists of two objects (r and s), and another to indicate the total size of the encoding. Finally, an additional byte at the end of the signature indicates the signature hash type, which is used by Bitcoin to determine which parts of a transaction to use when creating a signature. Overall, this results in seven extra bytes to encode the two 32-byte values r and s.

In theory, this should result in a total signature size of 71 bytes. In practise, however, several points must be considered. First of all, the fact that Bitcoin uses signed integers as data type has implications on the signature size: for, whenever r or s have their most significant bit (MSB) set, their encodings require an additional one-byte zero padding so they are not interpreted as negative numbers. Note that values that have their MSB set are also referred to as “high values,” whereas those that have the bit not set are referred to as “low values.”

Originally, no restrictions applied to r and s. Assuming uniform distribution of values, each number should have its MSB set half of the time, implying a 25% chance of no padding, a 50% chance of padding for exactly one of the values, and a 25% chance of padding for both values. In this case, signatures are expected to have an average size 72 bytes.

Today, however, several restrictions apply: Bitcoin Core 0.11.1 introduced the “low s” rule, which enforces that only transactions with low s values are relayed. Thus, s is guaranteed to require no padding; r, however, still requires padding half of the time, leading to an average signature size of 71.5 bytes. Newer implementations voluntarily implement the “low r” optimization, and create signatures that have a low r value as well. In this case, none of the values require padding, resulting in an average signature size of 71 bytes.

Finally, whenever an r or s value has eight or more of its leading bits set to zero, the respective value can be encoded using less than 32 bytes. The overall signature size can thus be smaller than the previously established averages.

To quantify the overall impact of the different factors influencing the signature size, an analysis of empirical data is in order. The histogram in Fig. 1b shows the incidence of different signature sizes over the course of the last two years. As expected, the bulk of signatures have a size of 71 or 72 bytes. The slight bias toward 71 bytes can be credited to the previously discussed “low r” optimization of state-of-the-art implementations. Moreover, a small amount of 70-byte signatures can be observed. These can be attributed to the previously discussed occurrence of leading zero bits in the binary representation of r and s values. In fact, there are even signatures with sizes of only 69 or 68 bytes; these, however, occur too infrequently to be visible in the histogram. The average signature size according to empirical data is 71.46 bytes, which is in line with the analytically estimate of 71.5 bytes established previously. Thus, for the following investigation, signatures are assumed to have a size of 71.5 bytes.

2) Encoding of Schnorr signatures: Schnorr signatures consist of a curve point, P, and a 32-byte value s. To save space, the signature only contains P’s 32-byte x-coordinate from which the corresponding y-coordinate can be derived (ambiguity concerning y is again addressed by implicitly using the y that is even). Unlike ECDSA, Schnorr signature encoding does not follow DER [5]: instead, the two 32-byte values, r and s, are encoded back to back without additional metadata. The size requirement for Schnorr signatures is thus 64 bytes.

III. TRANSACTION FORMAT

In the following, the general formats of transactions as well as transaction inputs, outputs, and witnesses are discussed, and the formats’ implications on transaction size are investigated.
A. Transaction format

All transactions include the following fields: a four-byte version, two variable-length integer (varints) to indicate the number of inputs and outputs, and a four-byte lock-time. Segregated Witness (SegWit) transaction include two additional bytes: a one-byte SegWit marker to indicate that the transaction includes witness data, and a one-byte SegWit version. Note that no additional varint is required to indicate the number of witnesses in the transaction, since the number of witnesses implicitly corresponds to the number of inputs.

Transaction-size estimates thus include a fixed eight-byte (or ten-byte, in case of SegWit) contribution; the size of the encodings of two varints; and the sizes of the inputs and outputs. Each witness contains a varint to indicate the number of items it contains. The items are of arbitrary size, so each item’s length is encoded using a varint as well.

B. Transaction input format

From a high-level viewpoint, each transaction input comprises two key pieces of information: a reference to an unspent transaction output (UTXO) and an unlocking script that satisfies the locking script of the referenced UTXO.

The UTXO reference consists of a 32-byte transaction identifier (TXID) to reference a previous transaction, and a 4-byte position number to indicate a particular output of the referenced transaction.

Unlocking scripts have a variable size, and their contents depend on the type of UTXO they are trying to spend. Script formats for different transaction types will be covered in the next section; for now, it is sufficient to note that the script’s size is encoded using a varint.

Finally, each input contains a 4-byte sequence number, which is currently used for the replace-by-fee mechanism that allows updating a transaction’s fee.

To summarize, the input size is made up a fixed component of 40 bytes, comprising the 32-byte TXID, the 4-byte position, and the 4-byte sequence number; and a variable one, comprising the unlocking script and the encoding of its size.

C. Transaction output format

Transaction outputs include two key pieces of information: an amount and a locking script.

D. Transaction witness format

Witnesses can serve as alternative stores for data to unlock outputs. Each witness contains a varint to indicate the number of items it contains. The items are of arbitrary size, so each item’s length is encoded using a varint as well.

IV. TRANSACTION INPUTS, OUTPUTS, AND WITNESSES

In the following, the inputs, outputs, and (where applicable) witnesses formats of the different transaction types are investigated. In each instance, the discussion begins with a first-principles-based analysis of size requirements; based on this, an estimate for the size requirements is derived, which is then verified using empirical data (including historical data in Bitcoin’s blockchain up until November 2020).

A. Pay-to-Public-Key

1) Outputs: The locking-script format used by Pay-to-Public-Key (p2PK) outputs is shown in Table I with σ_p, the size of the following public key; p, an SEC-encoded public key; and OP_CHECKSIG, the Bitcoin Script instruction for signature verification. The encoding of the key’s size requires one byte, the encoded key uses 33 bytes, and the Script instruction uses another byte, leading to a total script size of 35 bytes.

Together with the eight-byte amount and the one-byte varint to encode the locking script’s size, this leads to a total size of 44 bytes for p2PK outputs.

This analytic estimate is validated by the empirical data shown in Fig. 2, which contains a histogram of the sizes of p2PK outputs. Discounting 76-byte outputs, which are an artifact from Bitcoin’s early days when public keys were encoded using the uncompressed SEC format, all outputs match the analytic estimate of 44 bytes.

2) Inputs: The unlocking-script format used by p2PK inputs is shown in Table II with σ_s, the size of the following signature, and s, a DER-encoded signature. The encoding of the size of the signature requires one byte and the signature itself requires, on average, 71.5 bytes, leading to an average total script size of 72.5 bytes.
Also taking into account the 40 bytes for TXID, position, and sequence number as well as one-byte varint to encode the script’s size, this leads to an average input size of 113.5 bytes.

As before, the analytic estimate is validated by empirical data. Fig. 2(b) contains a histogram of the sizes of all P2PK inputs up to Nov. 2020. As expected, more than 90% of all inputs have a size of 113 or 114 bytes and thus match the estimate. Inputs with a size of 115 bytes are artifacts from a time when the “low s” rule was not enforced; inputs smaller than 113 bytes can be attributed to the occurrence of encodings of r and s with eight or more leading zero bits (cf. Sect. II-B).

B. Pay-to-Public-Key-Hash

1) Outputs: Pay-to-Public-Key-Hash (P2PKH) outputs the locking-script format shown in Table I with OP_DUP, the Bitcoin Script instruction to duplicate the top stack item; OP_HASH160, the Bitcoin Script instruction to apply the HASH160 function to the top stack item; 20, the size of the following hash; h, a 20-byte HASH160 of a public key; OP_EQUALVERIFY, the Bitcoin Script instruction to make the transaction invalid if the two top stack items differ; and OP_CHECKSIG, the Bitcoin Script instruction to verify a signature.

The four Bitcoin Script instructions and the encoding of the size of the hash require one byte each. Together with the 20-byte hash, this leads to locking-script size of 25 bytes.

Taking into account the eight-byte amount and the one-byte varint to encode the size of the locking script, the total size of P2PKH outputs is 34 bytes. As before, this analytic estimate is corroborated by empirical data, shown in Fig. 3a. The data indicates that all P2PKH outputs have a size of 34 bytes.

2) Inputs: P2PKH inputs use the unlocking-script format shown in Table I with σ_s, the size of the following signature; s, a DER-encoded signature; σ_p, the size of the following public key; and p, a SEC-encoded public key.

The encodings of the sizes of the signature and the public key require one byte each, whereas signature and public key require 71.5 and 33 bytes, respectively, leading to an average unlocking-script size of 106.5 bytes.

Considering the 40 bytes for TXID, position, and sequence number as well as a one-byte varint to encode the unlocking script’s size, this results in an average input size of 147.5 bytes.

The estimate is supported by empirical data shown in Fig. 3b. As expected, the majority of inputs have a size of 147 or 148 bytes. As before, small deviations from the estimate can be attributed to the DER encoding. The second cluster around 180 bytes is an artifact from Bitcoin’s early days where public keys where encoded using the uncompressed SEC format.

C. Bare Multi-Signature

1) Outputs: The (bare) multi-signature (MS) locking-script format is shown in Table II with OP_m, indicating the number of signatures required to satisfy the locking script; σ_p, and p_j, the sizes and encodings of n public keys; OP_n, indicating the number of public keys; and OP_CHECKMULTISIG, the MS-validation Script instruction.

The Script instructions contribute three bytes, the encoding of the size of each of the n public keys contributes one byte, and each public key 33 bytes. This results in a locking-script size of 34n + 3 bytes. Together with the eight-byte amount and the one-byte varint to encode the script’s size, this results in a size of 34n + 12 bytes for m-of-n MS outputs.

This analytic estimate is verified for 1-of-2 and 1-of-3 MS outputs, which together amount for more than 98% of all MS outputs. The estimates are 80 and 114 bytes, respectively. The empirical data shown in Fig. 4a supports these estimates: the bulk of 1-of-2 and 1-of-3 MS outputs have a size of 80 and 114 bytes, respectively. In each case, there is a smaller number of outputs that are 32 bytes larger than the estimate—artifacts from old transaction using the uncompressed format in which public key’s include the 32-byte y-coordinate.

2) Inputs: The MS unlocking-script format is shown in Table III with OP_0, a dummy Bitcoin Script instruction to address a bug in the implementation of OP_CHECKMULTISIG; and σ_s, and s_i, the sizes and encodings of m signatures.

The Script instruction contributes one byte, the encodings of the size of the m signatures one byte each, and each signature, on average, requires 71.5 bytes. This results in an average unlocking-script size of 72.5m + 1 bytes. Also considering the 40 bytes for TXID, position, and sequence number and...
null data outputs

D. Null Data

1) Outputs: The Null-Data locking-script format is shown in Table I with \texttt{OP\_RETURN}, the Bitcoin Script instruction to indicate an unspendable output; \( \sigma_d \), the size of the following data; and \( d \), the data included in the output. Note that as of Bitcoin Core 0.12.0, only 80 bytes of data are allowed.

The Bitcoin Script instruction contributes one byte. The encoding of the data’s size requires one or two bytes\(^6\) and the actual data requires \( \sigma_d \) bytes. The locking-script size is thus \( \sigma_d + 2 \) for data smaller than 75 bytes and \( \sigma_d + 3 \) for larger data. Combined with the eight-byte amount and the one-byte varint to encode the script’s size, this results in an output size of \( \sigma_d + 11 \) for outputs that include up to 75 bytes of data, and \( \sigma_d + 12 \) for outputs with more data.

This analytic estimate is verified for 20- and 80-byte Null-Data outputs, which together account for more than 90% of all Null-Data outputs. The estimate for the former is 31 bytes; for the latter it is 92 bytes. These estimates are corroborated by the empirical data in Fig. 5.

E. Pay-to-Script-Hash

1) Outputs: The Pay-to-Script-Hash (P2SH) locking-script format is shown in Table I with \texttt{OP\_HASH160}, the Bitcoin Script instruction to apply the HASH160 function; 20, the size of the following hash; \( h_r \), a 20-byte HASH160 of a redeem script; and \texttt{OP\_EQUAL}, the Script instruction to determine whether the two top stack items are identical.

The Script instructions and the encoding of the size of the hash contribute one byte each; together with the 20-byte hash, this results in a total locking script size of 23 bytes. Together with the eight-byte amount and the one-byte varint encoding the script’s size, this leads to an output size of 32 bytes. This estimate is confirmed by the empirical data shown in Fig. 6a.

In contrast to fixed-size P2SH outputs, the size of P2SH inputs varies significantly depending on the type of redeem script included in the input. The most relevant use cases are discussed in the following.

2) P2SH-MS inputs: The P2SH-MS unlocking-scripts format is shown in Table II with \( d \), data corresponding to the signatures required to satisfy the redeem script; \( \sigma_r \), the size of the following redeem script; and \( r \), the redeem script. In case of P2SH-MS, the data, \( d \), follows the conventions for MS unlocking scripts documented in Table II whereas the redeem script, \( r \), follows those of MS locking scripts documented in Table I. In Sect. IV-C, the sizes for these scripts were established to be 72.5\( m + 1 \) and 34\( n + 3 \) bytes, respectively. In case the redeem script is smaller than 76 bytes, the encoding of its size, \( \sigma_r \), requires one byte; in case it is larger, two bytes.\(^6\) The unlocking scripts used in \( m\text{-of-}n\)-P2SH-MS inputs thus have a size of 72.5\( m + 34 n + 5 \) bytes for redeem scripts smaller than 76 bytes, and an extra byte in case of larger redeem scripts.

Together with the 41-byte contribution of \texttt{TXID}, position, sequence number, and the encoding of the script’s size, this leads to an estimate of 72.5\( m + 34 n + 46 \) bytes for redeem scripts smaller than 76 bytes; larger redeem scripts are subject to additional overhead (discussed in more detail in the following).

These analytic estimates are verified for 2-of-2 and 2-of-3 P2SH-MS inputs, which together account for more than 90% of such inputs. For the former, \( n = 2 \), so the estimate for the redeem script’s size is 34\( n + 3 = 71 \) bytes. The encoding of the script’s size therefore requires only one byte. For \( m = n = 2 \), the estimate of the input’s size is thus 72.5\( m + 34 n + 46 = 259 \) bytes. For 2-of-3 P2SH-MS inputs, \( n = 3 \), and the average redeem-script size is 34\( n + 3 = 105 \) bytes, which means the encodings of the redeem script’s size requires two bytes.\(^6\) Together with the data to satisfy the redeem script, which requires 72.5\( m + 1 = 146 \) bytes, this leads to a total unlocking-script size of 105\( + 2 + 146 = 253 \) bytes. Because varints can only encode numbers up to 252 with a single byte, the encoding of the unlocking script’s size requires three bytes. Taking into account the contributions of the 32-byte \texttt{TXID}, the 4-byte position, the 4-byte sequence number, the 3-byte varint to encode the script’s size, and the 253-byte unlocking script, yields a total input size of 296 bytes.

The two estimates are corroborated by empirical data in Fig. 6b. Almost half of all 2-of-2 P2SH-MS inputs match the estimate of 259 bytes; signatures one byte smaller or larger than the estimate are explained by DER-encoded signatures being, on average, 71.5 bytes; absent the “low \( r \)” optimization, there is a 50% probability of generating either a 71-byte or 72-byte locking script.
The fact that the public keys’ sizes are encoded with a one-byte varint instead of a one-byte Bitcoin Script instruction does not affect the estimate.

| Type            | Witness |
|-----------------|---------|
| P2SH-P2WSH-MS   | $n_i \sigma_{w} \sigma_{r}$ |
| P2SH-P2WPKH     | $2 \sigma_{s} \sigma_{p}$ |
| P2WPKH          | $2 \sigma_{s} \sigma_{p}$ |
| P2WSH-MS        | $\eta_i \delta_{w} \sigma_{w}$ |
| P2TR (key path) | $\delta_{s}$ |
| P2TR (script path) | $\eta_i \delta_{w} \delta_{c}$ |
a total unlocking script size of 23 bytes. Together with the 32-byte TXID, the 4-byte position, the 4-byte sequence number, and one byte for the varint to encode the unlocking script’s size, this results in a total input size of 64 bytes. This estimate is validated by the empirical data in Fig. 9a, which confirms that all P2WPKH inputs have a size of 64 bytes.

6) P2SH-P2WPKH Witnesses: The P2SH-P2WPKH witness format is documented in Table III with 2, to indicate two witness items; \( \sigma_s \), a varint encoding the size of the following signature; \( s \), a valid signature for the following public key; \( \sigma_p \), a varint encoding the size of the following public key; and \( p \), the public key corresponding to the HASH160 hash used in the locking script. The three varints contribute one byte each, and the signature and key 71.5 and 33 bytes, respectively, making for a total witness size of 107.5 bytes.

This estimate is corroborated by empirical data shown in Fig. 9b, which indicates that more than 99% of all P2SH-P2WPKH witnesses have a size of either 107 or 108 bytes. The bias toward 107 bytes can be explained by the fact that the “low \( r \)” optimization, which results in 71-byte signatures in comparison to the 71.5-byte average used by the estimate, was already widely used by the time P2WPKH was introduced.

F. Pay-to-Witness-Public-Key-Hash

1) Outputs: The locking-script format of Pay-to-Witness-Public-Key-Hash (P2WPKH) outputs is shown in Table II with \( \text{OP}_0 \), the Script instruction to indicate a version zero witness program; 20, the size of the following hash; and \( h_p \), a HASH160 hash of a public key. The Bitcoin script instruction and the encoding of the hash’s size contribute one byte each, the last 20 bytes, resulting in a locking-script size of 22 bytes.

Together with the 8-byte amount and 1-byte varint to encode the script’s size, this results in an output size of 31 bytes. This estimate is validated by the empirical data in Fig. 9h, which confirms that all P2WPKH outputs have a size of 31 bytes.

2) Inputs: For P2WPKH, the data to satisfy the locking script resides in the witness, so the unlocking script is empty. P2WPKH inputs thus consist only of a 32-byte TXID, a 4-byte position, a 4-byte sequence number, and a 1-byte varint to indicate a zero-length unlocking script. Inputs thus have a fixed size of 41 bytes, a fact which is corroborated by empirical data shown in Fig. 9h.

3) Witnesses: P2WPKH witnesses contain the same data as P2SH-P2WPKH witnesses (cf. Table III): 2, to indicate two witness items; \( \sigma_s \) and \( s \), the size of and the corresponding signature; and \( \sigma_p \) and \( p \), the size of and the corresponding public key. Again, the varints contribute one byte each, the signature and public key 71.5 and 33 bytes, respectively, resulting in a witness-size estimate of 107.5 bytes.

The estimate is validated by empirical data shown in Fig. 9b, which shows that 99% of all P2WPKH witnesses have a size of either 107 or 108 bytes. As was the case for P2SH-P2WPKH witnesses, the fact that SegWit was introduced after the “low \( r \)” optimization explains the bias toward 107-byte witnesses (cf. Sect. IV-E6).

G. Pay-to-Witness-Script-Hash

1) Outputs: The Pay-to-Witness-Script-Hash (P2WSH) locking-script format is shown in Table II with \( \text{OP}_0 \), the Script instruction to indicate a version zero witness program; 32, the size of the following hash; and \( h_w \), the SHA256 hash of a witness script. The first two items contribute one byte each, the last 32 bytes, resulting in a locking-script size of 34 bytes.

Also considering the account the amount (eight bytes) and the varint encoding the script’s size (one byte), this results in an output size of 43 bytes. This estimate is validated by the empirical data in Fig. 10h, which confirms that all P2WSH outputs have a size of 43 bytes.

2) Inputs: For P2WSH, the data to satisfy the locking script resides in the witness, so the unlocking script is empty, as was the case for P2WPKH. Inputs thus have a fixed size of 41 bytes (cf. Sect. IV-F2). This estimate is corroborated by empirical data shown in Fig. 10h.

3) Witnesses: More than 98% of all P2WSH transactions are used for MS, so the following discussion focuses on P2WSH-MS. P2WSH-MS witnesses contain the same data as P2SH-P2WSH-MS witnesses (cf. Table III). The estimate for the witness size is thus identical as well and corresponds to 72.5m + 34n + 6 bytes (cf. Sect. IV-E4).

In the following, this analytic estimate is verified for 1-of-1, 2-of-2, and 2-of-3 P2WSH-MS witnesses, which together amount for more than 98% of all P2WSH-MS transactions.

For \( m = n = 1 \), the estimate is 112.5 bytes; for \( m = n = 2 \), it is 219 bytes; and for \( m = 2 \) and \( n = 3 \), 253 bytes. All estimates are supported by the empirical data shown in Fig. 10h. In all instances, the observed sizes match the analytic estimates. For the latter two variants, the bias toward smaller sizes can again be explained by the “low \( r \)” optimization (cf. Sections IV-E6 and IV-F3).
H. Pay-to-Taproot

Since Pay-to-Taproot (P2TR) is not yet available, estimates in this section cannot be validated using empirical data.

1) Outputs: The P2TR locking-script format is shown in Table I with OP_1, the Script instruction to indicate a version-one witness program; 32, the size of the following hash; and p, a 32-byte tweaked Schnorr public key. The first two items each contribute one, the last 32 bytes, resulting in a locking-script size of 34 bytes. Adding the 8-byte amount and one-byte varint to encode the script’s size, yields an output size of 43 bytes.

2) Inputs: The data to satisfy the locking script resides in the witness, leaving the unlocking script empty. As in case of P2WPKH (cf. Sect. IV-F2), inputs thus have a size of 41 bytes.

3) Witnesses: P2TR locking scripts can be satisfied either by key path (i.e., by providing a valid signature for the tweaked public key in the locking script) or script path (i.e., by providing a valid input, a corresponding witness script, an untweaked public key, and hashes of the leaves and branches of the Merkle tree required to determine the tree’s root).

In case of the key path, P2TR witnesses comprise: 2, the number of witness items; σ,s, the size of the following Schnorr signature; and s, a Schnorr signature. The two first items are varints that contribute one byte each, and a Schnorr signature uses 64 bytes in case of the default signature hash type and 65 bytes in case of a custom signature hash type. Absent empirical data, the witness-size estimate will be based on the assumption that the default signature hash type is used in most cases. The P2TR key-path witness-size estimate based on this hypothesis is, therefore, 66 bytes.

In case of the script path, P2TR witnesses comprise: n,t, the number of witness items; d, data to satisfy the script presented next; σ,w, the size of the following witness script; w a witness script to be interpreted as locking script; and c, a control block (the first byte of the control block encodes the leaf version, which in case of the script path is always 0x00; the next 32 bytes encode an untweaked Schnorr public key; finally, the control block holds one or more 32-byte blocks that encode the hashes of the leaves and branches of the Merkle tree that are necessary to reconstruct the Merkle root used to tweak the public key).

V. AUTOMATING TRANSACTION-SIZE ESTIMATES

libtxsize integrates the previously established and empirically validated analytic models to estimate the size, virtual size and weight of arbitrary transactions. In addition to overall estimates, libtxsize can provide information about a transaction’s components, such as the sizes of individual inputs, outputs, and witnesses, as well as transaction overhead.

The library is available on GitHub and uses a bottom-up approach to create estimates: first, if necessary, the sizes of redeem and witness scripts are estimated to determine the size requirements of the Bitcoin Script instructions and varints that encode the lengths of such scripts; next, the script and witness sizes are calculated, taking the results of the previous step into account. Once the script and witness sizes are known, the size of the Bitcoin Script instructions and varints to encode their length are determined, and other constant contributions of inputs (TXID, position, and sequence number) and outputs (amount) are considered. Finally, the sizes of all inputs, outputs, and witnesses are assembled, and the transaction overhead (transaction version, two varints indicating the number of inputs and outputs, lock time, and, if applicable, SegWit marker and version) is added.

The library is written in Python and exposes Python interfaces to get estimates for input, output, and witnesses sizes, as well as estimates for transactions. libtxsize also includes a command-line interface to facilitate quick experimentation.

VI. RESULTS AND CONCLUSION

The formats of Bitcoin transactions, inputs, outputs, and witnesses were presented. Moreover, the sizes of different input, output, and witness types were investigated using first-principles analysis, from which analytic estimates were derived. A summary of these estimates is presented in Table IV. Furthermore, all estimates (with the exception of Pay-to-Taproot, for which no empirical data is available so far) were validated using empirical data.

Finally, libtxsize, a library that makes the findings easily accessible by automating estimates for the size, virtual size, and weight of transactions and their components, was presented.

REFERENCES

[1] J. Lopp. Bitcoin transaction size calculator. [Online]. Available: https://floop.github.io/bitcoin-transaction-size-calculator/  
[2] Bitcoin Optech. Transaction size calculator. [Online]. Available: https://bitcoinops.org/en/tools/calc-size/  
[3] Buy Bitcoin Worldwide. Bitcoin fee calculator & estimator. [Online]. Available: https://www.buybitcoinworldwide.com/fee-calculator/  
[4] C. Research. “Standards for efficient cryptography, SEC 1: Elliptic curve cryptography,” September 2000, version 1.0.  
[5] International Telecommunication Union, “Information technology — as.n.1 encoding rules — specification of basic encoding rules (ber), canonical encoding rules (cer), and distinguished encoding rules (der),” ITU-T Recommendation X.690, July 2002.  
[6] Bitcoin Wiki (various authors). Bitcoin Script — Constants. [Online]. Available: https://en.bitcoin.it/wiki/ScriptConstants

---

8https://github.com/virtu/libtxsize