# Supply Chain Integrity Using Spectral Signatures with Blockchain

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***Abstract*— We describe and evaluate a novel method for material and food safety and integrity in the supply chain using FTIR/NIR spectral signatures embedded concurrently in both a traditional supply chain management tool as well as within a distributed ledger block in blockchain. The blockchain provides a tamper proof ledger, while the spectral signatures ensure the authenticity of the material itself. By the use of these technologies in addition to encryption and clustering for waveform classification, we provide an end-to-end supply chain integrity solution. The solution is implemented as a proof-of-concept with state of the art IoT (for handheld spectral measurement devices) with Blockchain and SCM software within a Platform as a Service Cloud, to provide an unique multi-disciplinary solution.**

***Keywords—FIR/NIR Spectra, Blockchain, cloud computing, supply chain integrity, food safety, Internet of Things***

## I. Introduction

Supply chain integrity for material safety and provenance continues to be an important area of research interest. Issues such as degradation, contamination, and substitution have a serious bearing on financial costs, business reputation, public health and well-being. Supply chain logistics professionals continue to be concerned about identification of points in the supply chain where such problems might occur for quick remediation or supply chain forensics. Some of the questions that are important as a product moves along the supply chain are:

1. How to uniquely identify and fingerprint the content of raw materials (foods such as olive oil, cheese; pharmaceuticals and raw materials) along different points in the supply chain?

2. How to record this unique fingerprint at each point in the supply chain in a tamper-proof manner in a ledger that is both transparent to audit while at the same time, prevents tampering of the records along the supply chain?

3. How can such an approach be implemented with recent advances in IoT and Cloud?

Our novel approach described above, builds on the latest technologies in each of the areas above, and creates a robust and precise solution for supply chain integrity. The first issue is addressed through the use of Fourier Transform Infra-red (FTIR) and Near Infra-Red (NIR) spectra to uniquely identify and fingerprint the content of materials as it travels through the supply chain. The second problem is solved by recording each transfer in the supply chain as an immutable blockchain transaction between the parties, with the spectral signatures recorded on the block along with other details regarding that transaction. The third issue is addressed with the use of advanced IoT and encryption to record and transmit the spectral data; as well as cloud technologies for supply chain management: processing and auditing the blockchain ledgers for supply chain integrity. We will review prior research in each of the above areas followed by our contributions to each of the steps above in creating this multidisciplinary solution for supply chain food safety.

## II. REVIEW OF PRIOR TECHNOLOGY

### *A. Blockchain Technology in Supply Chains*

A Blockchain is a ledger implemented as a distributed database of records updated and audited through consensus. The records may be transactions or events among participating entities, which are shared and visible to all parties on the blockchain. Each transaction is verified by consensus of special participants in the system assigned for verification and validation. When the method of consensus is proof of work, these special participants are known as miners. The blockchain is immutable in the sense that once a transaction is entered, information cannot be erased or altered since the hash of the subsequent blocks depends the hash of the previous blocks as well as their contents. Therefore, the blockchain is said to contain a verifiable and immutable record of every single transaction ever made. Bitcoin, the decentralized peer-to-peer digital currency, is the most popular example that uses blockchain technology.

Blockchain has evolved significantly beyond its origins as the technology underlying the Bitcoin. It has been applied to banking, finance, and supply chains, among others. Underlying this technology, we will focus on the two aspects particularly relevant to our work:

1. A distributed peer-to-peer technology without a central point of control, allowing multiple stake-holders to participate in the update and audit of the blockchains.

2. The immutability, and tamper-proof nature of hashing functions used in the blockchains that makes it difficult to change any single block (and therefore contents of the transaction) independently- either by accident or through malicious intent.

One of the key characteristics of blockchains that have made them powerful in many applications is their tamper resistance to changes in individual transactions already added to the blockchain. The spectral signatures to be described in the next section provide a unique way to identify the content of the shipment at a point of receipt in the supply chain. The blockchain technology, then provides for a way to record these supply chain transactions (including spectral signature details) in a tamper-proof manner so that the flow of material from source to destination can be audited (particularly when degradation/contamination is detected at the consumer end of the supply chain).

There are many on-going efforts in the use of blockchains for supply chain provenance, and [14, 15, 17, 24] are but a representative sample. Prior work in research and practice for provenance provide frameworks where transactions along the supply chain are updated with shipment information such as bill of materials, tags etc. The blockchain is auditable by stakeholders in the supply chain such as producers, retails, wholesalers, shippers, importers and regulators. While some as in [24], use BlockVerify tags to avoid counterfeiting, others use bill of material records, SKU stamps and similar product identifiers. Inspection is performed by means of visual or automated scanning to record a transaction at any given point in the supply chain.

Our work, extends the current work on blockchain for provenance in supply chains. In addition, it posits that simply using billing and transactions records, packaging or additional markers, identifiers and tags on products, while useful in proving provenance, may not be sufficient in many cases (such as in the milk powder contamination, or replacement of claimed high end ingredients with differently sourced ones). Further such documentation are themselves prone to counterfeiting.

In many cases, provenance (the example of supplements or food materials), may require point-to-point tracking (not just at the source or destination) of actual spectral signatures of the material involved in the transactions in order to both deter, and to identify any adulteration, contamination, degradation or replacement of the product during transit from origin to consumer. The FTIR/NIR fingerprints of the material itself recorded in a blockchain, at each point add yet another layer of security, especially in cases where existing techniques may not prove sufficient or are deemed too weak.

### *B. Spectral Signatures of Materials*

Validation of a supply chain via FTIR/NIR spectral signatures of an organic or inorganic product has been used in various areas including manufacturing, agriculture, pharma, retail, and automotive; and usually may involve multiple questions of interest. A buyer of a product along a supply chain (originator, shipper, wholesaler, retailer, or consumer) may want to verify:

1. Contents (that is the ingredients of a product are actually what was claimed), and that there was no adulteration or contamination along the supply chain. And if there indeed was a change, they might like to know the location of such contamination both as deterrent and as a method for tracking.
2. Degradation of the quality of products, such as in food products due to improper

handling along the supply chain. This may include improper temperature/refrigeration, handling, and sealing.

3. Sourcing and provenance (that is the product was not substituted in whole or in part along the supply chain, even with very similar contents). Examples may involve provenance for fair-trade, environmental issues, regional authenticity, farm raised versus wild, pesticide use, supplement contamination nut allergies, etc.
4. Regulation: In a multi-part supply chain, regulators may want to track sources with risks, or quality (for example, even though medication may have named ingredients, whether they are in the approved proportions for example).

Vibrational spectroscopic methods such as FTIR (Fourier transform) spectroscopy are emerging as powerful techniques in monitoring adulteration and authenticity of foods, pharmaceuticals, agricultural, and chemical products. FTIR (Fourier transform infrared) spectroscopy is a well-established analytical technique for rapid, high-throughput, nondestructive analysis of a wide range of sample types, providing a fingerprint characteristic of chemical or biochemical substances present in the sample. Advances in FTIR instrumentation and multivariate techniques have shown potential for analysis of complex multispectral information for the discrimination, classification, quantification, and identification of various compounds. FTIR is the most commonly used vibrational technique for material identification and authentication and when coupled with attenuated total reflectance (ATR) simplifies the spectral collection from solids, liquids, semisolids, and thin films. ATR is a reflection technique in which the IR light is reflected internally off the back surface of an internal reflection element with a high index of refraction, which is in contact with the sample. When light is passed through a sample some of the wavelengths of light are absorbed whereas others are transmitted. The molecules in the sample undergo mechanical motions (vibrational and rotational modes) which cause a change in the distribution of charge (dipole) across the molecule due to the absorption of energy. This is the case for most covalent chemical bonds and therefore most organics are known to be 'IR active'. A wide range of inorganics are also IR active such as nitrates, phosphates, chlorates and sulphates. In FTIR, light absorption by the sample is measured across a range from 400 – 4000 $cm^{-1}$ (or 25000 – 2500 nm) corresponding to fundamental molecular vibrational modes. A plot of % absorbance, transmittance or reflectance against wavenumber is termed an 'IR spectrum'. Absorptions corresponding to the vibrational frequencies of different bonds within the molecule can be used to identify a particular functional group e.g. - OH, -NH, -CH, -SH, -CN, -CO, -CS and versions of C-C as the positions of these bonds in the IR range are well known. Because of complex interactions of atoms within the molecule, each involved in its own vibrational transitions, the energy of a vibration and, thus, the position of the band in the IR spectrum are sometimes influenced by the atoms surrounding the vibrational group. Thus, the IR spectra can be unique and used to identify or differentiate between samples and also give information about the quantity of functional groups. The ability of IR spectroscopy to reveal qualitative and quantitative characteristics about the nature of chemicals, their structure, interactions, and molecular environments provide unparalleled capabilities for detection of contaminants and adulterants in foods, pharmaceuticals, agricultural, and chemical products. Advantages of approaches based on vibrational spectroscopy include low operational cost, small size, compactness, robustness, high throughput, ease of use, and minimum background training to operate. FTIR spectroscopy can provide rapid and specific tools for analysis of chemical contaminants and for the reliable assessment of quality and safety enabling monitoring of raw material stock during transit and storage to determine if substitution, adulteration, or degradation has occurred and determination of authenticity upon arrival.

FTIR and NIR technologies have been widely used in the agriculture and other industries [5, 6] to validate content. Food and pharmaceutical safety are some of the areas in which these technologies are used. With advances in hardware miniaturization and embedded analysis, these devices have become amenable for use in supply chain logistics. In addition there is open source literature on detecting signatures in food. A small but representative subset of literature in the field of detecting spectral signature in food include [4, 5, 6]. For example, in [8], the spectral signature of melamine which was implicated in the China Milk Scandal [9] is given to be observed in a milk protein. The quality of various medical supplements (such as gingko) are investigated with spectral analysis in [11]. In their results, there is validation of the significant concern among supplement consumers (since supplements are not FDA regulated) regarding their quality and sourcing. [10] Shows the use of spectral analysis for detection of e-coli contamination in foods. This may be important for regulators when they have to act quickly to identify particular points in the supply chain where contamination occurred. Similar signatures are obtained for commonly occurring foods such as olive oil, orange juice, wine and cheese.

### *C. Supply Chain Integrity, Trust and Robustness*

Supply chain security, integrity and trust are especially critical in many industries such as pharmaceuticals and food supply. There are both human exposures and financial risks [27, 29, 32] with respect to these aspects. Ensuring this integrity and safety, requires a multi-disciplinary approach. This requires research in many aspects of supply chain logistics and the existing literature spans multiple areas including operations research, logistics theory, financial analysis, economics and trade, IT automation, among others. For the purposes of the paper, we have only cited a few representative examples from literature [25-34] to show breadth in the area.

The importance of communication, co-operation and integration in supply chain management has been studied in [26]. These factors are important at all levels of supply chain from human behaviors, logistical to IT automation, operations and service delivery. Co-operation, communication and integration are well exemplified by the blockchain protocols and therefore the technology is ideal to being applied to supply chain provenance.

It is increasingly common for supply chain logistics and traceability approaches to use cloud technologies [35], and leverage big data technologies [36, 38] to improve quality and cost of management. The move towards open source ecosystems into supply chain information systems [37] will help standardize technologies for analysis and improved tracking, since software and APIs will converge.

The state of the art technologies for ensuring provenance in the supply chain such as RFID read by IoT devices in the field; and the use of supply chain management tools is well established from an IT perspective [28]. The use of blockchain opens new ways of securing critical supply chains, and are ideally suited for the modern globally distributed, and integrated supply chains. Innovations in IR IoT and cloud further extend the ability to communicate and co-operate in distributed environments.

### *D. Cloud Technology and IoT for Food Safety*

There have been significant advances in hand-held FTIR/NIR spectrometers. Data from such meters may be transmitted directly to the cloud for analysis. At the cloud several software as a service technologies are available: open source and proprietary software can be integrated and deployed with quick turnaround time. Open Source supply chain management (SCM tools) are provided as SaaS (Software as a service), Open Source blockchain software and services, such as Hyperledger, Ethereum and others are available and have advanced significantly as well. Services such as Twilio as a cloud service enable communication from the IoT device to the cloud via SMS. It is now possible to create and provide a fully integrated service from source (FTIR spectrometers in the supply chain), with direct transmission for processing and audit in the cloud. In addition to using the various technologies, the development of an integrated service is one of the practical contributions of this work.

## III. SPECTRAL ANALYSIS

### *A. Contamination of Material Along Supply Chain*

Edible oils such as olive oil, canola oil, sunflower oil, corn oil, nut oil begin to decompose when they are isolated from their natural environment. Changes can occur which can cause a disagreeable taste, smell and appearance. Atmospheric oxidation is the most important cause of deterioration. This oxidative rancidity is accelerated by exposure to heat, light, humidity and the presence of trace transition metals. During transit and storage, product may be exposed to excessive heat, light and/or humidity. Other possibilities include defective or broken packaging which allows exposure of the sample to oxygen and moisture. Spectroscopic methods such as near infrared (NIR) spectroscopy and Fourier Transform Infrared (FTIR) spectroscopy provide quick and accurate method of determining if degradation of a sample has occurred either during transit or storage.

To simulate possible degradation due to excessive heat, a virgin sample of canola oil was used for frying and exposed to high heat in atmospheric conditions in a cast iron skillet. The intense heat of frying is known to cause an oxidizing thermal degradation in oils with the formation of decomposition products [1]. Changes in the FTIR spectra of canola oil was observed after heating the canola oil during frying. FTIR spectra were collected utilizing a Nicolet 6700 (Thermo Nicolet, Madison, WI) and spectra were analyzed utilizing OMNIC software (Version 7.0 Thermo Nicolet) included in the FTIR spectrometer. Using a Pasteur pipette, an approximately of 0.5 mL of oil samples was properly placed on attenuated total reflectance (ATR) crystal for spectra collection. The spectra of canola oil before and after frying are shown in Fig. 1. Both spectra show the typical characteristic absorption bands for common vegetable oils. The weak peak in the region 3500-3400 $cm^{-1}$ is attributed to O-H stretching from moisture in the canola oil. The peaks 1, 2 and 3 in the region 3,100–2,800 $cm^{-1}$ are due to C—H stretching mode. The C=O stretching is observable in the region 1,700–1,800 $cm^{-1}$. The wavenumber region 1,400–900 $cm^{-1}$ (peaks 4-8) are associated with C—O—C stretching and C—H bending [2, 3]. Changes in the spectra are observed after frying. As shown in Fig. 1 a reduction in the absorption intensity for peaks 1, 3, 4-8 and broadening of absorption peak 2 (increased full width half maximum) was observed. Changes in peak 1 are significant because this peak is attributed to the stretching vibration of the C-H link adjoin the C=C of polyunsaturated fats and is used to determine the unsaturation of edible oils. The infrared spectra show how frying produced a composition change in the oil resulting in a decrease in the unsaturated component and subsequent decrease in the oils nutritional and monetary value.

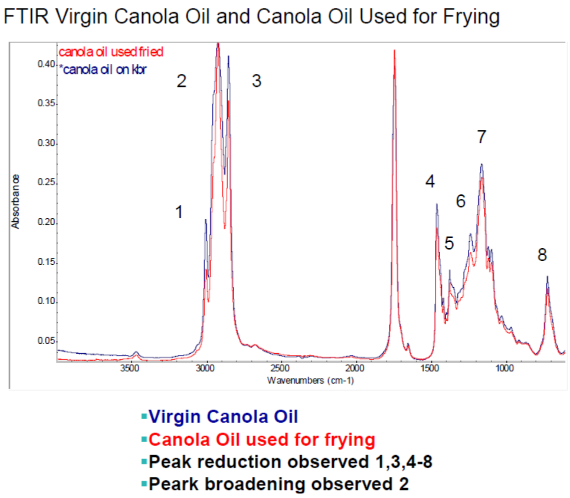


Figure 1. FTIR Measurements of Degradation

### B. *Adulteration of Sample Along Supply Chain*

Authenticity is a very important quality criterion for edible oils and fats. Because there is a big difference in prices of different types of oil and fat products, adulteration typically involves the replacement of high-cost ingredients with cheaper substitutes. In our example, we have adulterated virgin coconut oil with canola oil. Virgin coconut oil is typically priced 10-20 times higher than common plant oils such as canola oil. Spectroscopic methods such as near infrared (NIR) spectroscopy and Fourier Transform Infrared (FTIR) spectroscopy can provide quick and accurate method of determining if adulteration of a sample has occurred.

Shown in Figure 2 is a comparison of the FTIR spectra of unadulterated virgin coconut oil and a 1:1 mixture of virgin coconut oil and canola oil. FTIR spectra were collected utilizing a Nicolet 6700 (Thermo Nicolet, Madison, WI) and spectra were analyzed utilizing OMNIC software (Version 7.0 Thermo Nicolet) included in the FTIR spectrometer. Using a Pasteur pipette, an approximately of 0.5 mL of oil samples was properly placed on attenuated total reflectance (ATR) crystal for spectra collection. Both spectra show the typical characteristic absorption bands for common vegetable oils. The weak peak 1 in the region 3500-3400 $cm^{-1}$ is attributed to O-H stretching from moisture in the canola oil which is not observed in virgin coconut oil. The peaks 2, 3, 4 and 5 in the region 3,100–2,800 $cm^{-1}$ are due to C—H stretching mode. The C=O stretching is observable in the region 1,700–1,800 cm-1 (peaks 6 and 7). The wavenumber region 1,400–900 $cm^{-1}$ (peaks 8-12) are associated with C—O—C stretching and C—H bending. However, Compared with other edible fats and oils such as canola oil, virgin coconut oil has unique FTIR spectra [1,2,3]. Peak 1 attributed to moisture is not observed in virgin coconut oil nor is there an absorption at 3009 (peak 2) and 1655 (peak 7). Furthermore, at frequency region of 1120 - 1090 cm-1, VCO showed one weak (11) while canola oil exhibited two peaks (11 and 12). These differences can be exploited to determine if adulteration of virgin coconut oil has occurred. As shown in Figure 2, after addition of 1:1 canola oil to coconut oil, new peaks 1,2,5,7,12 are observed, while the peaks 3 and 4 broaden and are reduced in intensity, and peak intensity is increased for peaks 6,8,9,10, and 11.

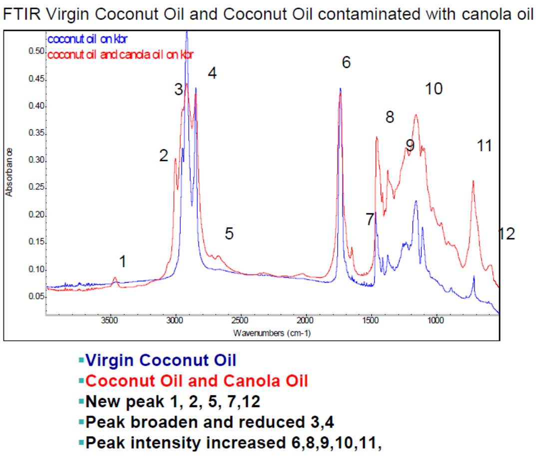


Figure 2. FTIR Measurements of Contamination

At least three key characteristics of the spectra will be used as signatures where necessary and record on the blockchain.

1. Peak Intensities (select a number N, or a threshold)
2. Wavelengths at which the peaks occur
3. FWHM (Full Width at Half Maximum) at the peaks

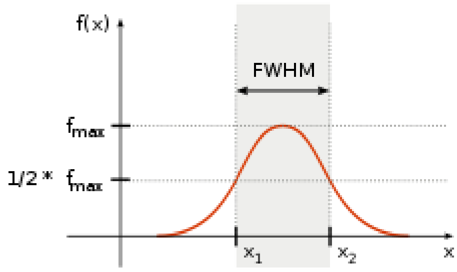

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Figure 3. Characteristics of Spectra

In later sections, these will be used as features in the clustering and identification of anomalous spectral signatures.

## IV. SUPPLY CHAIN WITH BLOCKCHAINS

We will demonstrate the use of blockchains for supply chain integrity using the open source Hyperledger technology. We will use a sample of Coconut oil outlined above which is adulterated at a certain point with Canola oil along the supply chain as indicated in the previous section. The simple illustrative supply chain we will use as a running example shown in Figure 4, will have six points along the chain. The producer of coconut oil, an aggregator, an exporter, a shipper, an importer and a retailer. Each of these actors will update the SCM tool whenever they receive a shipment. This entire supply chain will have a supply-chain-id, and each shipment will have a shipment-id, which will be recorded as part of the transaction, in addition to sampled spectral signatures of the material received. The SCM tool automatically updates the blockchain for the shipment. Any of the actors described above can choose to audit the blockchain to verify the spectral signatures during transport.

Each transaction in the supply chain is added to the blockchain along with key characteristics of the spectral signature at the point of receipt of shipment. The addition of the block occurs through a process of consensus by the miners shown in Figure 4. Consensus may use traditional proof of work methods in public blockchains or use other consensus algorithms as in private blockchains. This step of validation of the block by the miners is a blockchain concept, in that the validity of the hash of the blocks is verified, and at this point the miners don't validate the spectral signatures. Later examples of the approach shown will include miners that mine both the blocks for validation, as well as the spectral signatures. But these are independent concepts: one involves validation of blockchain blocks by miners so as to be able to add the blocks to the chain, the second involves checking the spectra which is part of the audit of the blocks already on the blockchain.

As in all cases of quality control, the merchandise received may be sampled, and a few samples may be chosen for spectral inspection. For example in Figure 4, when the coconut oil is transferred from the producer to the aggregator, a record of the bill of materials, and receipts are recorded in the blockchain as a block. In addition, on the same block, a record of the spectral signature of the sampled material is recorded. The addition of more transactions along the supply chain proceeds in a similar manner, rendering the previously added blocks tamper proof since the hash of the current transaction block is derived based on that of the previous one. The sample blockchain with three blocks is shown in Figure 5. Note that each block is based on the hash of the previous block. The TX denotes the transaction content, which may include any information including spectral signatures. In our example, the spectral signature is stored as key/value pairs of wavelength/absorbance at small but fixed intervals. The key/value pairs for a block corresponding to each transfer point is stored as a JSON string in that block.

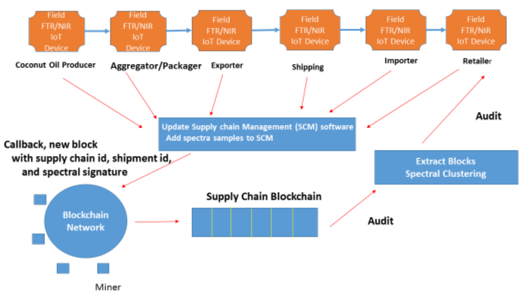


Figure 4. Supply Chain Methodology

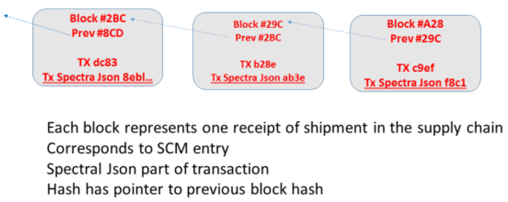


Figure 5.Sample Blockchain Entries

In summary, Fig 4. Illustrates the following two roles:

1. **Actions of each shipment recipient in the supply chain include:**

In the Supply Chain Management Tool, make an entry for shipment received with SCM tool shipment id, and supply chain id.

Add spectral samples to that entry.

Automatically add the same transaction information from the Supply Chain Management Tool including the spectral information onto a blockchain along with the corresponding shipment id and supply chain id. Once entered on the blockchain, the spectral signatures cannot be tampered with.

2. **Actions of an auditors (stake holders) for the supply chain:**

Get all blockchain ledger entries for a supply chain id, and if required a particular shipment id of concern.

Compare spectral information for each shipment received using clustering to distinguish significant changes to waveforms.

Flag points of change to indicate: contamination, replacement or degradation.

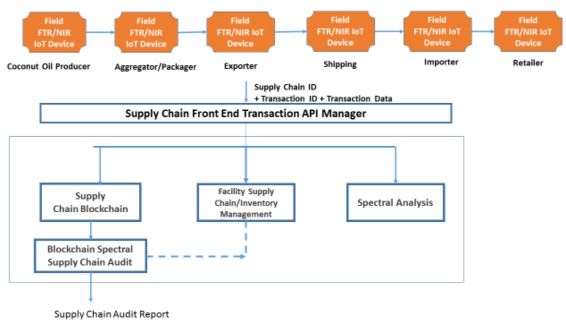


Figure 6. Supply Chain Integrity Methodology

Figure 6. Shows a cloud based methodology with a single API for transaction entry, a

separate API for audit, and different software blocks that perform the functions. In later sections, operation and implementation details of each of the blocks will be discussed.

Each transaction along the supply chain is incorporated as a standard block in a blockchain by the miners. In our case, the transaction in addition would contain an encrypted version of FTIR or NIR signature (s) as measured by the sender, a set of signatures (s) as measured by the receiver. There are several ways (with increasing complexity) with which the FTIR or NIR signatures can be incorporated into the block. We will describe them below to illustrate the range of possibilities.

The simplest approach is the addition of FTIR/NIR signatures as part of the transactions to each block in the blockchain. The ledger records in an immutable manner, all the FTIR/NIR signatures along the supply chain. In the first approach, the miners may choose to just verify the integrity of the transaction record alone (not verify NIR signature but just treat it as transaction data) before adding it to the chain. One example would be for the sender A of a product to submit the sending spectral identifier set (there may be one or more), encrypted to the miner without being able to see the content of the message (sent directly from the device). The receiver B, does the same, where they send the spectral identified set, encrypted to the miner. The miner, will match the two spectral identifier sets within a reasonable bound of error for that set. The miner in addition may need to perform proof of work on both submitted transactions to verify the authenticity of the messages, and to establish consensus with the other miners. .

An additional approach is that the miners in addition, will verify that the FTIR/NIR signatures match within an allowed margin or compare to a set of valid spectral signatures (based on expectations for a particular product that the miners know about) and arrive at a consensus on whether the signatures were valid, and record the results along with the block. This is shown in Figure 7.

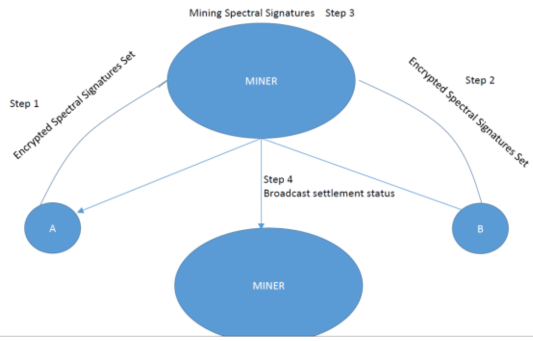


Figure 7. Supply Chain Transaction Mining

A third approach where the FTIR/NIR generator device will only produce an encrypted signature not possible for anyone to decrypt (neither the sender nor receiver in the transaction), except the miners who will have the key. This is to avoid, fraud where the sender may use old signatures previously known to be valid for a product. This is shown in Figure 8.

In a fourth approach: a product tag, and the FTIR/NIR spectrum together generate a combined encrypted signature. This adds another level of security, and incorporates existing tags into the flow.

A fifth approach is where along with a product tag is an encryption which the NIR measuring device needs to solve, in order to validate that it actually measured the product with that particular tag. This prevents sending of previously recorded (and approved) spectral signatures.

Another approach is where a sender adds a tag (which combines the product id), which requires proof of work at the receiver. The additional signature will be incorporated into the sender's signature.

An additional, approach would be to query a unique identifier for an established spectral hash code from a SPLASH bank [7]. There is an effort at standardization of spectral signature for materials in the same manner as InChIkey is designed to serve as a unique identifier for chemical structures. The spectra many be converted into an unique code with a hash representing the material (say caffeine) and only the hash value may be stored, therefore reducing the space and analytics requirements. This is a lossy compression of data and should be only selected based on requirements of audit and expected issues along the supply chain.

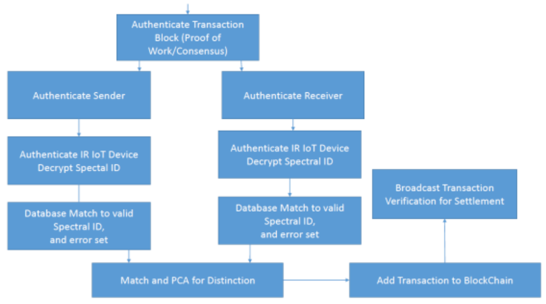


Figure 8. Supply Chain Transaction Blockchain Update

## V. CLUSTERING TO CLASSIFY SPECTRA

In Figures 1 and 2, waveforms can be distinguished using visual inspection where at supply chain point 4 (the shipper), the change occurred in our example. Visually, distinguishing changes to spectral waveforms are easier when the changes are significant, but in real world supply chains, these changes to the waveform can be small, gradual, or such distinctions have to be made in noisy data. In addition in a high volume supply chain, these distinctions will need to be made in an automated fashion.

A variety of techniques to precisely cluster and classify waveforms are available. Techniques such as Principal Component Analysis (PCA) and Clustering are generally used [19, 20, 21]. For our purpose, we use an agglomerative clustering technique. Hierarchical clustering techniques such as agglomerative, have been used to cluster and classify waveforms for areas as diverse as audio, cardio and astronomy. We evaluate such a method for spectral waveforms from the materials in question.
Two waveforms with minor changes (not significant from the point of view of spectral changes) are used as baseline waveforms: Waveform1 and Waveform2. Waveform3 gives the contaminated spectra. A noise source is added to all the waveforms to model the inaccuracies in the real world due to measurement errors or minor changes in the material which are part of the supply chain characteristics. Based on an agglomerative clustering analysis, we find the Euclidean or Manhattan metric are found to be the most suitable as shown in Figure 9. While this method is not too sensitive (0.84 versus 1.0 interclass affinity), it is sufficient for our purpose. Future work involves identifying more sensitive clustering methods.

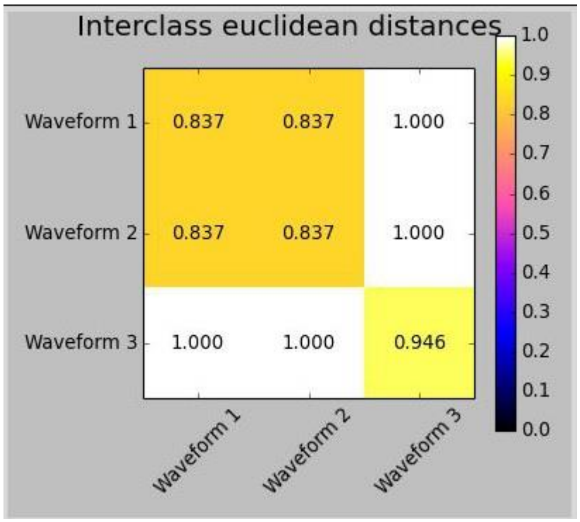


Figure 9. Agglomerative Clustering of Spectra with Euclidean Distance

Observing waveform drift over time: While the previous clustering techniques are suitable for distinguishing changes along the supply chain for any one given shipment in the chain; another requirement for auditors is to understand the changes in waveforms that may occur during the lifetime of the supply chain relationship. Over the years, a product may change in quality, or be impacted by changes in supply chain logistics. Detecting slow and gradual drift in the waveforms across large amounts of waveform data is of interest to auditors as well. In Figure 10, the gradual drift in the spectral signature of the material is plotted over the years. This helps highlight either the change in quality due to deliberate contamination, or identify the effects of changes in the handling methods (for example in shipping suppliers, temperature, storage facilities) etc. which may be contributing to the degradation of the quality of the material (in this case coconut oil). By observing such change quarterly, or yearly, the method described provides a way to perform quality control. The presence of these signatures in tamper proof blockchains over the years, guarantees the integrity of this data.

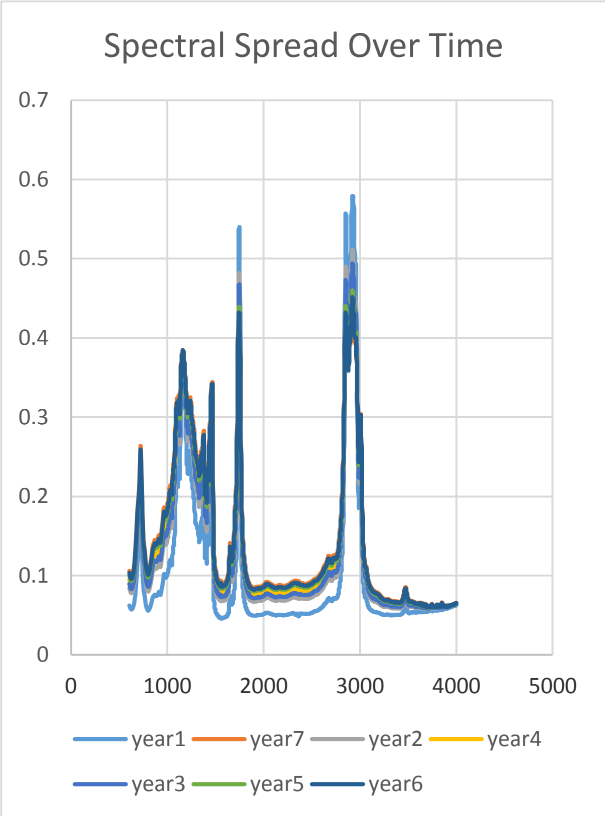


Figure 10. Spread of Spectral Signatures over Supply Chain Relationship

## VI. CLOUD AND IOT TECHNOLOGIES

Various technologies enable the integration of the concepts and methodology in prior sections into an integrated methodology. Docker container based software enable quick bring up and restart of the software such as Apache Ofbiz and Hyperledger. The Hyperledger implementation consisted of a four-peer blockchain network, a smart contract in Go, a nodeJS server for HTTP API requests, and a HTML front end. The Agglomerative clustering was performed in a separate container with APIs to the JSON using the python scikit-learn library. The cloud based implementation with the modules instantiated with open source software is shown in Figure 11.

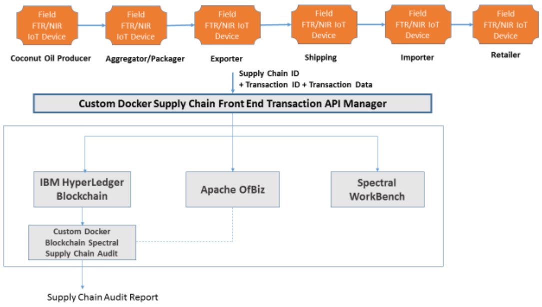


Figure 11. Implementation with IoT and Cloud Technologies

## VII. IMPLEMENTATION METHODOLOGY DEMONSTRATION

In our implementation methodology, the data obtained by the IoT (handheld FTIR spectrometers) are sent to the cloud as JSON files, where the wavelength and absorbance are key value pairs. These JSON files then form the basic data structure that represent the spectral signatures that are obtained and updated to a cloud service at each point of receiving of the supply chain.

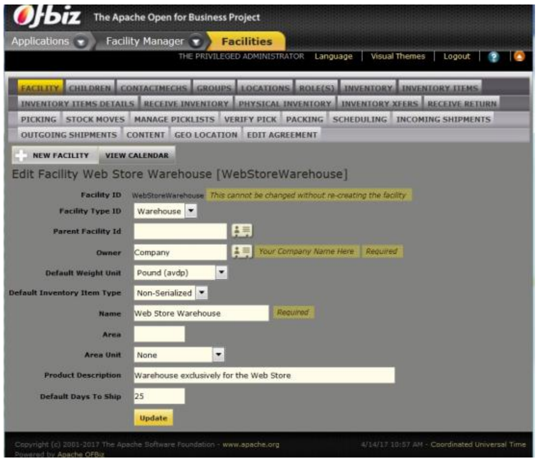


Figure 12. Apache Ofbiz Supply Chain Front End

For the proof of concept, as each supply chain transaction is updated in our SCM tool of choice - Apache Ofbiz (selected due to open source availability), a concurrent update is also made into a blockchain in the Hyperledger. A sample front end of the Apache OfBiz facility manager which includes warehouse, facility and inventory management is show in Figure 12. A four-peer blockchain is deployed in Hyperledger using docker-compose to start the containers required for the network [22, 23].

The blockchain deploy therefore creates the ledgers and the nodes. The blockchain ledger is the basic data structure and history of all successful state. It is constructed by the ordering as a totally ordered hashchain of *blocks* of transactions. A block is implemented as a key, value store of blobs that can be updated and queried via a *put* and a *get* transaction respectively. The hashchain imposes the total order of blocks in a ledger and each block contains an array of totally ordered transactions.

The nodes are communication entities that participate in the update of the ledger data structure. They enable the validation and consensus required to update the blockchain. There are different types of nodes in Hyperledger, the two primary ones being: client and peer. In our four-peer blockchain, each peer can update the blockchain as well as maintain a copy of the state and the ledger. When a deploy transaction executes successfully, the nodes are deployed and active as docker containers, and the chaincode has been initialized "on" the blockchain.

This blockchain network is updated and queried via chaincode (or smart contract) implemented in the Go language. The client represents the entity that acts on behalf of an end-user. It must connect to a peer for communicating with the blockchain. The client may connect to any peer of its choice. Clients create and thereby invoke transactions. An *invoke* by a client (used by a receiver in the supply chain) of a transaction in the Hyperledger smart contract will add a block (along with the JSON of the specified spectral signature) onto the blockchain. A *query* transaction by the client (used by an auditor) in the smart contract will give a list of all the blocks in the blockchain that match a given supply chain id and shipment id. The invoke is used for updating the blockchain and the query for audit purposes. We store and retrieve spectra JSONs into and out of the blocks on the blockchain within the chaincode (smart contracts) by Marshalling, and Unmarshalling in the Go language.

A nodeJs web server provides the REST API services to the smart contract (chaincode), and interfaces with a client HTML front-end for update and audit. The HTML front end on the client side uses D3 for display of the spectral waveforms as shown in Figure 13. These tools have been used for prototyping and proof of concept purposes, a production version will use other proprietary tools. The Python scikit-learn module is used for reporting clustering results on the server side. This module is implemented as a separate container.

## VIII. LIMITATIONS AND FUTURE WORK

While this work opens up new ways of enabling supply chain integrity, we see further opportunities for new research in the technology development for this area.

1. While we have picked the non-invasive method of spectroscopy, other more invasive methods described in [4] such as isotope analysis, DNA analysis chemometric analysis, metabolomics etc. still remain available as options, and would benefit from further exploration with blockchain and integration into cloud based methodologies.
2. More sensitive clustering and classification for spectral waveforms will be investigated with particular focus on gradual degradation of materials.
3. A future version of the proof of concept methodology described in this document is planned to be hosted on our corporate Production Platform as a service.
4. Combining the spectral hash with the blockchain hash to create a stronger protection that combines the two methods.

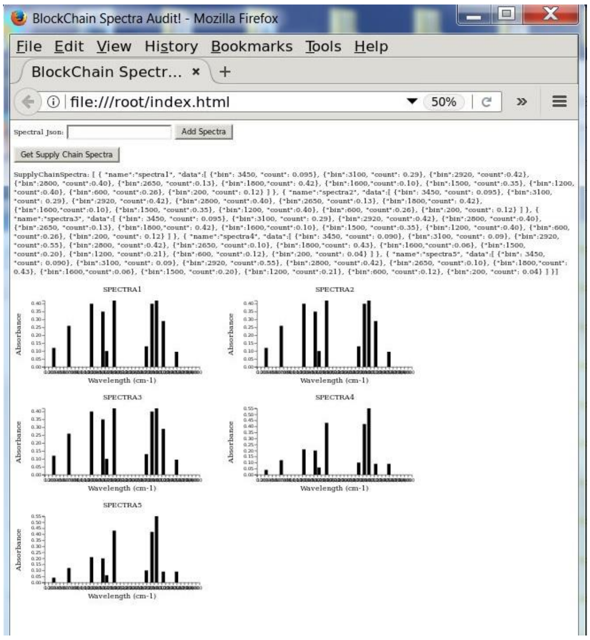


Figure 13. Audit Query from Hyperledger NodeJS Server and D3 Display

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